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# Potassium Reduces $^{137}Cs$ in Food Crops Grown on Coral Soils: Coconut at Bikini Atoll


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## Errata

McInroy, J. F.; Gonzales, E. R.; Miglio, J. J. Measurement of thorium isotopes and $^{228}Ra$ in soft tissues and bones of a deceased Thorotrast patient. Health Phys. 63(1):54–71; 1992.

The authors and editorial staff regret an error in the spreadsheet used for the calculation of the thorium and radium concentrations of the ribs (1–12) reported in Table B-6 (page 69). The corrected values are:

**Table B-6.** Weights, thorium isotopes and radium concentrations of bones and parts of bones of the entire skeleton.

| | Weight (g) | | Thorium and radium concentration ($Bq\ kg^{-1}$ ash) | | | |
|---|---|---|---|---|---|---|
| Skeletal part | Wet | Ash | $^{232}Th$ | $^{228}Ra$ | $^{228}Th$ | $^{230}Th$ |
| Ribs (1–12) | 448 | 131 | 7179 | 3150 | 2764 | 908 |

All other numbers in the table remain the same.

We apologize for any inconvenience or confusion these errors may have caused the readers of *Health Physics*.

## Errata

Robison, W. L.; Stone, E. L. The effect of potassium on the uptake of $^{137}Cs$ in food crops grown in coral soils: Coconut at Bikini Atoll. Health Phys. 62(6):496–511; 1992.

The authors and editorial staff regret that a typographical error went undetected throughout the review of this paper. On page 500, a conversion was listed as 1.0 Bq $^{40}K \approx 22.27$ mg potassium; the correct conversion is 1.0 Bq $^{40}K \approx 32.8$ mg potassium. We apologize for any inconvenience this error may have caused the readers of *Health Physics*.

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# POTASSIUM REDUCES $^{137}$CS IN FOOD CROPS GROWN ON CORAL SOILS: COCONUT AT BIKINI ATOLL

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Abstract—The soils of Bikini Atoll (11° 35'N, 165° 25'E) were contaminated by fallout from a thermonuclear explosion in 1954. Today, in the absence of any treatment, intake of $^{137}$Cs via the terrestrial food chain could account for 70% of the radiological dose received by a returning population. Therefore, we examined the effectiveness of potassium (K) applications, alone and combined with nitrogen (N) and phosphorus (P), in reducing $^{137}$Cs uptake by coconut (*Cocos nucifera L.* ), a major food crop. Mean pre-treatment concentrations of $^{137}$Cs in "drinking-nut" meat of ~17-yr palms ranged from ~0.5 to 7.0 Bq $g^{-1}$ (wet wt.) in the seven primary experiments reported. These values were reduced to ~0.06 to ~1.0 Bq $g^{-1}$ following soil additions of KCl at rates from 670 to 6270 kg K $ha^{-1}$. Major reductions were complete within nine to twelve months after single large applications and persisted for at least three years. Reductions in associated drinking-nut fluid and mature "copra nut" meat were both proportional. Comparable but shorter-lived reductions occurred in grass and herbaceous species beneath the palms. A combined NP treatment had no additive effect in the presence of K but, by itself, significantly reduced plant uptake of $^{137}$Cs. Periodic additions of K at rates of ~1000 kg $ha^{-1}$ would provide a feasible and highly effective means of reducing $^{137}$Cs in coconut-food products.

## INTRODUCTION

A thermonuclear device, code-named "BRAVO", detonated at the northwest end of Bikini Atoll, March 1, 1954, resulted in radioactive deposition on the northern and eastern islands of the atoll. Thus, the resulting current inventory of $^{137}Cs$ in the soil of the two principal residential islands, Bikini and Eneu, represents an aged source term.

Natural environmental processes have redistributed the surface-deposited radionuclides. In the case of plant-absorbed elements, downward movement has been countered in some degree by recycling through vegetation (Koranda et al. 1978). In addition, numerous construction operations during the subsequent years of testing, followed by clean-up and resettlement activities after 1969, caused large scale disturbance of the surface soil. The generalized pattern of $^{137}Cs$ distribution in soil, a logarithmic decrease downward, is similar on both islands, (Fig. 1) despite a nearly ten-fold difference in concentration.

Detailed information on the radionuclide concentrations in foods and soil at Bikini have been given in Robison et al. (1982a, 1988), together with the potential radiological dose via all exposure pathways for people resettling the atoll. In the absence of any treatment, $^{137}Cs$ would be responsible for more than 90% of the estimated dose (Robison et al. 1982a; Robison 1983) with more than 70% of the total via the terrestrial food chain. Locally grown coconut would be a major contributor. The second most important pathway would be external exposure from $^{137}Cs$ gamma radiation. Thus, either eliminating $^{137}Cs$ from the soil column or reducing its uptake by food crops would substantially reduce the estimated dose to inhabitants and profoundly affect decisions about resettlement options.

In this paper, we report results from a series of experiments demonstrating marked reductions in $^{137}Cs$ concentrations in coconut following application of potassium (K) in potassium-containing fertilizers. We also observed a lesser suppressive effect associated with phosphorus (P) application.

## BACKGROUND

Soils of deep ocean atolls differ from most continental soils in that the mineral matrix consists almost solely of sand and coarser-size particles of calcium carbonate, as calcite and aragonite, containing small amounts of substituted Mg and Sr. Organic matter content of the surface layer varies from a trace to more than 10% and is the sole source of cation-exchange capacity. Silicate clays appear undetectable although trace amounts from global dust presumably occur. Analyses of three representative profiles from the stable island interiors illustrate the range in chemical properties of well developed soils (Table 1). All are calcareous with proportions of total Mg and Sr varying in accord with biological origin and weathering intensity. Organic matter is relatively high in the surface but decreases abruptly through a narrow transition zone. Calculated C/N ratios are about 10: to 13:1 indicating an advanced stage of decomposition. Total phosphorus is highly variable in amount, representing input by nesting sea birds at some time in the past

Total K in atoll-soil materials is low; the average for several atolls reported by Fosberg and Carroll (1965) is only 300 mg $kg^{-1}$. Exchangeable or extractable K is highest in the 0 to 5 cm layer, a result of both spray input and cycling by vegetation, but diminishes rapidly downwards (Table 1).

The concentration of stable Cs in sea water is about $3 \times 10^{-10}$ g $kg^{-1}$ (*vs.* $3.9 \times 10^{-4}$ g $kg^{-1}$ for K). Hence, both the total and exchangeable quantities in atoll soils must be very small, although analytical data are lacking. Maximum total concentrations of $^{137}Cs$ in the Bikini surface soils now range between 0.5 and $3 \times 10^{-12}$ g per g (Fig. 1, Table 1), or about eight orders of magnitude lower than the maximum surface concentrations of extractable or exchangeable K (Table 1; also Stone in Emery et al. 1954). Only 3 to 5% of the $^{137}$Cs remaining from 1954 is exchangeable, even with sequential extractions (Robison 1991). Although this appears contrary to expectations based on laboratory studies of cation exchange, such studies usually involve solution concentrations of $10^{-1}$ to $10^{-3}$ M, and analytical accuracies to perhaps $10^{-4}$. Hence retention of any cation in the range of $10^{-12}$ would be undetectable.

It is known that addition of K to nutrient solutions containing Cs greatly reduces uptake of the latter element (Middleton et al. 1960; Cline and Hungate 1960; Handley and Overstreet 1961; Nishita et al. 1962; Wallace et al. 1983). Where both elements are available, plants selectively absorb K and discriminate against Cs. In K-deficient media, Cs acts as a replacement for K, but only to a limited degree, with plants failing well short of maturity (Menzel 1954; Middleton et al. 1960; Cline and Hungate 1960; Wallace 1970; Wallace et al. 1983). These findings have only limited relevance to Bikini soil-plant systems, however, in view of the very wide ratio between available forms of the two elements there. Likewise, the extensive literature on $^{137}$Cs retention in soils with silicate clays is largely irrelevant to atoll soils. Of the greater interest is the evidence that Cs bound to organic matter, although largely non-exchangeable, is far more available for plant uptake than is Cs retained by clays (Barber 1964; Menzel 1965; Fredriksson et al. 1966; D'Souza et al. 1972; D'Souza et al. 1980). This is borne out by the high plant-soil concentration ratios observed at Bikini and other atolls of the northern Marshalls (Robison et al. 1982a,b, 1988). Ratios of 1 to 5 ($^{137}$Cs, Bq $g^{-1}$ green plant: $^{137}$Cs, Bq $g^{-1}$ dry soil) contrast with values of *ca* $10^{-1}$ to $10^{-3}$ reported in Ng et al.'s (1982) extensive review of non-atoll soils.

Although a suppressive effect of added K on plant uptake of $^{137}$Cs from atoll soils seemed highly probable, the only prior evidence known to us was that of the

University of Washington investigators (Walker et al. 1961; * Walker 1984). This was based almost entirely on pot culture studies of soils from Rongelap Atoll which also was contaminated by BRAVO fallout.

## METHODS

### *General*

Field studies and sampling were conducted during quarterly to semi-annual visits to the atoll. Eight successive studies (Table 2) were established in bearing coconut groves. The groves, of a large-fruited variety originally from Yap Island, had been planted in 1970 to 1972 after clearing existing vegetation. Tending of groves ended in 1978. Thus, each of our experiments entailed clearing of regrowth shrubs and volunteer coconuts. Use of a bulldozer caused some degree of soil disturbance. Ordinary commercial fertilizers were broadcast on the soil surface, either entirely at the beginning of a study or periodically, as described in Table 2. Regrowth of competing shrubs was controlled occasionally, either by mechanical crushing, mowing or hand clearing.

Samples were collected prior to the first application of fertilizers and usually at three- to six-month intervals thereafter. The basic coconut sample was a composite of five to eight "drinking nuts" from an individual palm. As not every palm bore nuts at the drinking stage at each collection period, the numbers of sampled palms per experiment or plot often varied. Mature copra nuts were sometimes collected in the absence of drinking nuts or, on two occasions, paired with drinking-nut samples from the same palms for comparative purposes

The husked nuts were opened in the field, and the fluid (liquid endosperm) from each measured and pooled. Both opened nuts and fluid were frozen within three to

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* Walker, R.B. Personal communication. University of Washington, Seattle, WA; 1984.

four hours and transported in that condition to Lawrence Livermore National Laboratory (LLNL) for analysis of $^{137}Cs$ and other gamma-emitting nuclides.

*Laboratory*

At LLNL the nuts were cracked and the meat removed, dried by lyophilization, and ground in a Waring blender. The meat was packed into 8.0-cm diameter x 4.6 cm-height aluminum cans. The fluid was first reduced in volume by evaporation and then canned for analyses. Most gamma analyses were performed in the LLNL facility, which consists of 14 high resolution solid state detectors and multichannel analysers. Blind duplicates and standards were included in each sample batch with a requirement that agreement be within 10% for acceptance. Similar quality-control standards and cross-counting at LLNL were imposed on those samples analyzed at other laboratories. In some instances $^{40}K$ determinations were used to estimate total K (0.037 Bq $^{40}K \approx 0.824$ mg K). However, shorter counting times suitable for $^{137}Cs$ often yielded erratic or non-reproduceable $^{40}K$ values for individual samples, contributing heavily to the variances of population means.

All $^{137}Cs$ and $^{40}K$ concentrations of coconut and other plant material were converted back to an original wet weight basis, except as otherwise specified.

*Field Experiments*

Experimental design, treatment and plot size varied over the nine years of installation (Table 2); specific descriptions follow:

Experiment I

As an outgrowth of initial monitoring efforts, a single four-palm plot, 25.6 x 25.6 m, was fertilized with a complete NPK fertilizer on 10 occasions over a three-year period (Table 2). A slow-release fertilizer, "Osmocote-Tropical," consisting of plastic-encapsulated pellets, was chosen to ensure a continuous nutrient supply between successive visits. Sampling had begun prior to the first application and still continues. Untreated, less intensively monitored palms nearby serve as informal controls.

Experiments II and III

These are parallel installations on Eneu and Bikini Islands, respectively. For each, four or five well separated palms were selected from previously monitored populations to represent about the maximum ranges of $^{137}Cs$ in drinking nuts. A combined fertilizer, usually 1:1 Osmocote and readily soluble 16-16-16, was broadcast 13 times over a 8.5-m radius around each palm.

Experiment IV

Two contiguous blocks of 17.1- x 94-m plots, each separated by either one or two 8.53-m wide untreated strips, were established in a ~ 4-ha area of newly cleared grove. The selected area represented the highest average $^{137}Cs$ surface-soil concentrations on Bikini Island, 2.6 to 3.7 Bq $g^{-1}$ (70 to 100 pCi $g^{-1}$), as determined by a 1978 aerial radiological survey (Tipton and Miebaum 1981). The design was factorial: two rates of applied K, with and without addition of a combined N-P treatment, in two blocks (Table 2). The fertilizers were distributed with a small battery-driven centrifugal spreader mounted on the back of a truck. Several passes were required to distribute the designated quantities The fertilized strip was 17.1 m wide, extending from the trunks of one 10-palm row to those of a third row, with only the center row (fertilized on both sides) being sampled until the 33rd month of the study. Four equal applications were made between February and December 1985.

The original experimental design was terminated at 33 months. At that time, the 8.5-m wide separation strips on either side of the $K_1NP_0$ and $K_1NP_1$ plots in one block were treated with KCl at the $K_1$ rate, thus doubling the previous plot width. Doing so extended K-treated soil to the edges of $K_0NP_1$ plot, which was between the other two, and hence to 8.5 m from the $NP_1$ sample row. Eleven months later, paired samples of drinking nuts and copra nuts were collected from individual palms in all of the original plots.

Three plots remained unaffected by the further treatment at 33 months and again at 51 months when Exp. IV was converted to Exp. VIII. Mean $^{137}Cs$ values from these plots are shown as an extension of the 0–33 month data.

In addition to coconut samples, bulk samples of a dominant understory grass, *Eustachys petraea* (Sw.)Desr., were collected from each plot at 9, 18, 21 and 30 months. Entire stems were clipped above the ground line along plot centers. Fleshy leaves of moonvine, *Ipomea macrantha* R&S, were also collected on the first three dates. The bagged samples were frozen and transported to LLNL, where they were oven-dried, ground and analyzed, as described for coconut meat.

Experiment V

One year after the area of Exp. IV had been cleared, 25 palms in an unused margin were rated individually for apparent vigor and fruitfulness. Ten were selected and assigned randomly to one of two treatments, a control, and "super-K"—an application of 6270 kg K $ha^{-1}$ aimed at maximizing the magnitude and rapidity of $^{137}Cs$ decrease. Single palm plots, ~8.53- x 8.53-m square, were created by subsoiling about 80 cm deep midway between rows in both directions. This is below the depth of most horizontal roots and so restricted absorption from the surface soil to within plot boundaries. Subsequent observations of root regrowth led to subsoiling again at 12 and 24 months and at six month intervals thereafter

The small plot size required hand spreading of the coarse-crystal KCl. To increase uniformity, the total per plot was divided into thirds and each third spread over the entire plot by a separate worker.

Experiment VI

Other studies demonstrated that coconut roots extend radially to at least 24 m, with large numbers of absorbing roots outside the 8.53-m minimum radius of treatment in Exp. IV. Thus, we established Exp. VI, aimed at maximizing the width of treated soil surrounding the sampled palms, within the limitations of the grove area then available. Each of the two sample plots consisted of two rows of five palms, surrounded by a similarly treated border, 17.1 m wide on the sides and 8.5 m on the ends. The treatments, 0 and 3940 kg K $ha^{-1}$, were randomized but unreplicated. Fertilizer distribution was as in Exp. IV.

Measurement of $^{137}Cs$ surface gamma emission prior to selection of this site indicated row means of ~7.74 to 10.3 nC $kg^{-1}$ $h^{-1}$ (~30 to 40 μR $h^{-1}$), only moderately less than in adjacent Exp. IV. Nevertheless, samples of drinking nuts proved much lower in $^{137}Cs$. Two palms at one end of the control plots were excluded from data summaries because their drinking nut concentrations were more than three standard deviations greater than the mean of all other untreated palms.

Experiment VII

The study design duplicates that of Exp. VI, but with palms much higher in $^{137}Cs$. The measurement plots were larger, four rows x five palms, with 17.1-m wide borders on all sides. The treatment rate, however, was much lower, 670 kg K $ha^{-1}$. The application was as in Exps. IV and VI.

Experiment VIII

As noted, Exp. IV was altered somewhat after 33 months by additional treatment in one block. The results prompted an expanded treatment

Accordingly, 51 months after establishment of Exp IV, the entire area was divided into four units or blocks that were separated by periodically subsoiling the boundaries to a depth of 70 to 80 cm. Two 0.64-ha units remained untreated and included four unaltered plots from original Exp. IV: $K_0$, $K_0$, $K_0$+NP, and $K_2$. The other two units, 0.64 and 1.9 ha in size, were treated overall with coarse-crystal KCl at the rate of 1120 kg K $ha^{-1}$, using a tractor-mounted "Vicon" spreader. As judged visually, distribution was excellent.

Samples collected immediately before and 12 months after this K application represent a variety of previous treatments. We have limited detailed analysis to only those unaltered "interior rows" of the originally designated Exp. IV plots and to only those palms that provided drinking-nut samples both at the time of refertilization (51 months) and 12 months thereafter. For present purposes we considered the palms as individual sample units, with paired before-and-after determinations of $^{137}Cs$.

*Data Analysis*

Experiments I, II and III have no formally designated controls but data from monitored unfertilized palms nearby assure that the large systematic reductions in $^{137}Cs$ concentrations occurred only after treatment.

ANOVAS of results from Exps. IV and V were conducted using SAS (SAS Institute, Inc. 1985). An initial ANOVA of the entire Exp. IV data set (33 months) by a repeated measures design revealed significant interaction between treatment and time, and between the K and NP treatments. Accordingly, further analysis was separate by each sampling time. These ANOVAs are based on weighted plot means inasmuch as the number of palms contributing varied, usually between 3 and 9. Duncan's Multiple Range Tests ($p = 0.10$) provide validation for the graphic presentations.

A separate ANOVA of drinking nut *vs* copra nut data collected at 42 months was conducted. The sample was limited to those palms bearing both drinking nuts and copra nuts. The relationships between copra nut meat and drinking-nut meat, and between copra nut meat and fluid were examined by regression analysis.

An earlier ANOCOVA of Exp. V demonstrated that large pre-treatment differences in $^{137}Cs$ among individual palms significantly affected post-treatment values, but only for the first five to nine months. Accordingly, the covariant was omitted from the present ANOVAs. The small and variable number of individual palms, three to five, contributing to each periodic mean indicated use of standard errors rather than Duncan's tests as measures of variation in the graphic presentations.

Standard errors for palms within plots are shown in the graph of Exp. VI and VII results. In view of the obvious effects of treatment, a planned "paired plot" analysis, before and after fertilization, within treatment, appeared redundant.

For Exp. VIII, the differences among means of the paired before and after samples were examined by unpaired "t" tests.

## RESULTS

Although drinking nuts were selected by Marshallese climbers, they represent a substantial range in maturity and volume of both meat and fluid, as well as $^{137}Cs$ concentration. A synthesis of various field and laboratory observations leads to the following view: $^{137}Cs$ concentrations in meat increase progressively from the earliest drinking-nut stage onward, with an eventual copra nut to "modal drinker" ratio of 1.6 to 1, as described later. Meat thickness increases and moisture content decreases during this development. Fluid volume increases for a time through the "young drinker" stage as the nut continues to enlarge but then decreases as the meat thickens. Fluid to meat ratios increase rapidly from around 0.2 to 0.25 to 1 in "young drinkers" with only traces of meat, to 0.5 to 0.7 to 1 in maturing copra nuts, finally approaching 1 to 1 in old copra nuts in which fluid no longer completely fills the nut cavity. Such changes contribute heavily to sampling variability in both drinking and copra nuts, among and within collection dates.

Experiments I, II, III

Variation among dates prior to treatment is due in part to a greater allowable range in what was then collected as "drinking nuts," and in part to unrecorded bulldozer clearing to facilitate access.

Although the three studies represent a wide range in pre-treatment $^{137}Cs$ concentrations, from ~0.37 to ~7.4 Bq $g^{-1}$ (~10 to ~200 pCi $g^{-1}$) in drinking-nut meat, the patterns of decrease after repeated applications of NPK fertilizers are similar (Fig. 2–4). The greater the initial concentration, the greater the absolute decrease to near-asymptotic levels characteristic of individual palms (Fig. 3,4). Palms initially low in $^{137}Cs$, ≤ 1.85 Bq $g^{-1}$ (≤ 50 pCi $g^{-1}$), reached the lowest $^{137}Cs$ activity levels, which often fell below those of naturally-occurring $^{40}K$ (~ 3 pCi $g^{-1}$)

The patterns for meat and fluid in Exp. 1 were similar (Fig. 2), with most of the decrease occurring by the time that half of the periodic fertilizer additions had been made. Figure 2 also demonstrates that $^{137}Cs$ in meat and fluid remained below ~0.15 and ~0.056 Bq $g^{-1}$ (~4 and ~1.5 pCi $g^{-1}$), respectively, for about six years, four of which follow the final application of fertilizer. Nevertheless, a gradual but continuing increase began three years after that final application. Soil samples taken 19 months after the first upturn reveal both the low organic matter at this site, (~ 3% at 0–15 cm, ~ 1% at 15–30 cm) and disappearance of added K (22 and 7 μg $g^{-1}$ exchangeable K at the two depths, *vs* 16 and 8 outside the plot).

Experiment IV

We attribute the abrupt decrease of $^{137}Cs$ visible in the controls at nine months, followed by appreciable recovery, to a "clearing effect" produced by extensive destruction of surface roots, plus localized shifting of the uppermost soil layers, plus off-site removal of some surface soil mixed with roots and stems of vegetation. Elsewhere, Morris et al. (1983) have quantified the loss of nutrient-rich topsoil by machine clearing intended to remove only coarse vegetation. Such a clearing effect must also be embedded in the apparent responses to treatment.

The first post-treatment samples were collected at nine months, thus representing a three- to nine-month response to only three of the four scheduled fertilizer applications (Table 2). The approximate minimum concentrations of $^{137}Cs$ (= maximum decreases) were reached six months later and remained constant until the end of the experiment at 33 months (Fig. 5a, b). The accompanying Duncan's test results are given in Table 3.

Although without apparent effect when combined with K, the NP treatment alone reduced $^{137}Cs$ in meat and fluid to about one half of the control levels. Both rates of K, with and without NP, reduced mean $^{137}Cs$ to about 0.67 to 0.93 Bq $g^{-1}$ (18 to 25 pCi $g^{-1}$) in drinking-nut meat, and to 0.22 to 0.37 Bq $g^{-1}$ (6 to 10 pCi $g^{-1}$) in fluid. Although some differences between rates of added K and/or presence of NP attain significance ($p = 0.10$) early in the experiment and at 33 months, the differences are minor. Essentially, the lower rate of K (1260 kg $ha^{-1}$) without NP is as effective as the higher rate or the combinations with NP.

Samples collected at 42 months reveal that doubling the fertilized width of the two $K_1$ plots 9 months earlier had further decreased $^{137}Cs$ in drinking-nut meat by 0.22 or 0.3 Bq $g^{-1}$ (6 or 8 pCi $g^{-1}$). This is evidence of root activity outside the originally fertilized 8.5 m band on either side of the sampled row. Likewise, $^{137}Cs$ in the $K_0NP$ measurement row, now only 8.5 m distant from K-treated soil on either side, decreased from ~3 to 1.7 Bq $g^{-1}$ (~80 to 45 pCi $g^{-1}$).

Thus, interpretation of the 42-month ANOVA must be limited to comparison of the control and $K_2$ treatments, neither of which was affected by plot width increases. The respective means for $K_0NP_0$, $K_2NP_0$ and $K_2NP_1$ are 5.3, 0.78 and 0.59 Bq $g^{-1}$ (142, 21 and 16 pCi $g^{-1}$) for drinking-nut meat and 2.1, 0.32 and 0.22 Bq $g^{-1}$ (56, 8.6 and 6.0 pCi $g^{-1}$) for fluid. All differences among the three values are significant by Duncan's multiple range test (p=0.10). The latter finding concurs with results of the Duncan's tests at 33 months (Table 3) and suggests that a small additive effect of the NP treatment may be emerging.

Results from the three unreplicated plots of the original Exp. IV indicate that the effects of NP and $K_2$ persist unchanged to about 53 months (Fig. 5a). Thereafter, the suppressive effects of $K_2$ appear to diminish and $^{137}Cs$ in drinking-nut meat from the $K_2$ treatment increases to 1.2 ± 0.19 Bq $g^{-1}$ (33 ± 5 pCi $g^{-1}$) at 63 months (Table 4).

Copra Nuts

At 42 months, concentrations of $^{137}Cs$ in drinking-nut meat over all treatments ranged from ~0.37 to 7.4 Bq $g^{-1}$ (~10 to ~200 pCi $g^{-1}$). Paired samples of drinking nuts and copra nuts from individual palms yielded the following regressions (expressed as Bq $g^{-1}$, wet weight):

$$^{137}\text{Cs (copra-nut meat)} = 1.60 \times {}^{137}\text{Cs (drinking-nut meat)},\ R^2 = .97$$

$$^{137}\text{Cs (copra-nut fluid)} = 0.52 \times {}^{137}\text{Cs (copra-nut meat)},\ R^2 = .96$$

Grass and Moonvine

Little grass was evident on the plots before the initial clearing, so the mixed grass cover present at nine months had spread from persistent stolons and seeds germinating after the first appreciable rains, seven months previously. Hard seeds of the deep rooted moonvine are omnipresent. As with coconut, the nine-month samples were collected just before the last of four equal fertilizer applications (Table 2).

The effects of treatment on $^{137}Cs$ concentration on the above-ground mass of grass resembled those on coconut over a period of 30 months, except for an initial decline in the controls from 83.3 to 28.5 Bq $g^{-1}$ (2250 to 770 pCi $g^{-1}$, dry wt.) (Fig. 6). After 30 months, however, $^{137}Cs$ in both the controls and NP treatments increased sharply, with less fluctuation thereafter. Mean concentrations in the eight K-treated plots were initially very low, ~1.85 Bq $g^{-1}$ (~50 pCi $g^{-1}$, dry wt.) but also increased markedly after 30 months (Fig. 6), indicating a diminishing effect of treatment. Further changes after 45 months are confounded by applications of K to 7 of the 8 previously K-treated plots and to one of the NP plots (described under Exp. VIII). This application reduced $^{137}Cs$ to 2.2 and 8.3 Bq $g^{-1}$ (59 and 225 pCi $g^{-1}$, dry wt.), respectively, whereas the remaining untreated plot values converged to a mean of ~38 Bq $g^{-1}$ (~1030 pCi $g^{-1}$, dry wt.).

Early observations indicated a denser grass cover on those plots receiving NP. Figure 7 gives no indication, however, that $^{137}Cs$ concentrations have been "diluted" by greater mass.

Unlike grass, $^{137}Cs$ in moonvine from the control plots did not decline in the successive collections at 9, 18 and 21 months. Nor were there clear trends of changes with time for the other treatments. Accordingly, values for the two replicates and three dates were combined as were those for K applications with and without NP.

The resulting means ± standard errors follow

| | | |
|---|---|---|
| $K_0$ | ($\underline{n}$ = 5) | 3.3 ± 0.37 Bq $g^{-1}$,(green weight) |
| $K_0$+NP | ($\underline{n}$ = 6) | 1.2 ± 0.15 Bq $g^{-1}$ |
| $K_1$ ± NP | ($\underline{n}$ = 12) | 0.63 ± 0.11 Bq $g^{-1}$ |
| $K_2$ ± NP | ($\underline{n}$ = 12) | 0.52 ± 0.074 Bq $g^{-1}$ |

Hence treatment effects in moonvine generally parallel those for grass and coconut. $^{137}Cs$ in moonvine leaves from the control and NP plots is much lower than in grass (when both are expressed on a wet weight basis), probably because moonvine roots are less concentrated in the extreme surface layer.

Potassium-40 measurements in both species indicated higher total K concentrations in the nine month collections, followed by declines. Accordingly, results from treatments and sample dates were aggregated to provide sufficient sample sizes for testing. Thus, the means (± S.E.M.) below are for $K_0$ over all sample dates, $K_1 + K_2$ at nine months, and $K_1 + K_2$ again at either 15 and 18, or 15, 18 and 21 months combined. The respective values (expressed as g $kg^{-1}$, green weight) are 3.9 ± 0.4, 6.3 ± 1.0 and 3.9 ± 0.15, for grass, and 1.4 ± 0.2, 4.3 ± 0.4, and 2.4 ± 0.2 for moonvine.

Thus, at 9 months, after application of only 3/4 of the scheduled amount of K, K concentrations had increased nearly two-fold in grass and three-fold in moonvine. By about month 18 to 20, however, plant concentration had returned to about the control level. Almost certainly this decrease was at least hastened by a period of excess rainfall, 1090 mm, in months 18–20. No large changes in $^{137}Cs$ accompanied this reduction.

Experiment V

ANOVAs over the entire treatment period indicate that decreases in $^{137}Cs$ in both meat and fluid are significant at p=0.012. With one exception, ANOVAs for individual sampling dates show significant treatment effects, mostly at p=0.05 to 0.01, beginning at 6 (meat) or 9 (fluid) months after the single large application of K. Levels of ~0.56 and ~0.22 Bq $g^{-1}$ (~15 and ~6 pCi $g^{-1}$) in meat and fluid, respectively, persist for at least 30 months (Fig. 7a, b).

The initial decline of $^{137}Cs$ in the control means cannot be due to a "clearing effect" inasmuch as site preparation, other than subsoiling to create single-palm plots, had occurred one year previously. Patchiness in availability of soil $^{137}Cs$ was large, however, as indicated by the range in drinking-nut concentrations before treatment, ~1.5 to 7.4 Bq $g^{-1}$ (~ 40 to 200 pCi $g^{-1}$). It appears that subsoiling, by severing all lateral roots outside the 8.5- x 8.5-m squares, eliminated uptake from some zones of high soil concentration.

The effective time required for major reduction in treated plots was less than the nine months indicated by Fig. 7a, b, inasmuch as the fertilizer was broadcast on dry soil (only 14-mm rainfall in the previous month), and only 42 mm fell in the succeeding two months. Thus, penetration of K into the upper soil was delayed. Nevertheless, first indications of a decrease in $^{137}Cs$ appear in the three-month samples.

Somewhat surprisingly, no obvious symptoms of stress appeared in coconuts subjected to the severe pruning of lateral roots, plus application of KCl at the rate of 12.5 metric tonnes per ha over the residual root system, plus limited rainfall in the following two months.

Experiment VI

The single, moderately large application of K (3940 kg $ha^{-1}$) was made to palms that proved to average only ~0.67 Bq $g^{-1}$ (~18 pCi $g^{-1}$) in drinking-nut meat. This mean was reduced to ~0.26 Bq $g^{-1}$ (~7 pCi $g^{-1}$) over a period of 15 months (Fig. 8). Fluid concentrations were likewise lowered to a mean of only 0.067 Bq $g^{-1}$ (1.8 pCi $g^{-1}$), which approximates activity due to the natural content of $^{40}K$.

The pattern of slow and gradual decrease contrasts with those of the other experiments. Relatively constant levels in the adjacent control plot demonstrate that the less drastic site preparation procedures employed had avoided any "clearing effect," such as noted for Exp. IV.

Experiment VII

Experiment VII is similar in design to Exp. VI, and only about 270 m distant, but differs in response (Fig. 9). Before treatment, $^{137}Cs$ concentrations in drinking-nut meat averaged about 4.8 Bq $g^{-1}$ (130 pCi $g^{-1}$) After application of 670 kg K $ha^{-1}$—the lowest total applied in these experiments—$^{137}Cs$ fell to ~1.4 Bq $g^{-1}$ (~38 pCi $g^{-1}$) in nine months and to ~0.96 Bq $g^{-1}$ (~26 pCi $g^{-1}$) after 15 months.

Experiment VIII

Fifty-one months after the initial addition of K to palms in Exp IV (42 months after the final addition), mean $^{137}Cs$ in drinking-nut meat ranged between 0.59 and 0.85 Bq $g^{-1}$ (16 and 23 pCi $g^{-1}$). Following a second application of 1120 kg K $ha^{-1}$, mean values in the same palms then decreased to 0.33 to 0.48 Bq $g^{-1}$ (9 to 13 pCi $g^{-1}$) at 63 months (Table 4). Neither the level of K nor the addition of NP in the original treatment had any further effect.

A similar decrease appears in the paired means from 67 palms representing eight border rows (hence, fertilized on one side originally) that were subsequently fertilized on the opposing side at 33 months, and then retreated. The mean (± s.d.) concentration of 0.80 ± 0.28 Bq $g^{-1}$ (21.5 ± 7.6 pCi $g^{-1}$) at 51 months fell to 0.42 ± 0.10 Bq $g^{-1}$ (11.3 ± 2.8 pCi $g^{-1}$) at 63 months.

Other values in Table 4 show the stability of $^{137}Cs$ over this period in palms unaffected by treatment. Mean values for palms initially treated at the $K_2$ rate—but not retreated—remained stable through 59 months at ~ 0.89 ± 0.15 Bq $g^{-1}$ (24 ± 4 pCi $g^{-1}$), but then increased to 1.2 ± 0.19 Bq $g^{-1}$ (33 ± 5 pCi $g^{-1}$) at 63 months indicating a decline in suppressive effect. This decline follows a second period of unusually high rainfall, with a total of ~ 1100 mm for months 52 through 55 (June–Oct, 1989).

## DISCUSSION

### *Potassium Effects in Coconut*

The patterns of $^{137}Cs$ reduction following K application are similar for drinking-nut meat, drinking-nut fluid and older or copra nut meat, although ratios among these vary with relative nut maturity. The near-identity of response to K and to K plus NP treatments (Figs. 5a, b) suggests that the reduction of $^{137}Cs$ in Exps. I, II, and III (Figs. 2,3,4) is due solely to the K component of the mixed NPK fertilizers applied. This indication is confirmed by the large reductions following other K-only treatments (Fig. 7, 8, 9).

Over all first-application experiments, the absolute decreases in drinking-nut $^{137}Cs$ due to K are greater where initial concentrations are greater, regardless of total amount of K applied. When the decreases are expressed as percentages of pre-treatment concentrations, however, all fall between 60 and 90%. In this case of Exps. IV, V and probably VII (Figs. 5, 7 and 9), such values (75, 89 and 81%, respectively) include some effect of clearing or subsoiling at installation of the study. Percentage decreases of $^{137}Cs$ in fluid are similar to those in meat. Perhaps coincidentally, the decreases following reapplication of K at 51 months averaged about 50% (Table 4).

The time required for major decrease in $^{137}Cs$ concentration in drinking nuts after K application is about nine months in Exps. V and VII (Figs. 7, 9), or somewhat less in the former when the lack of rain after treatment is considered. A comparable period of low rainfall after the first K application to Exp. IV probably influenced the time for major decreases (Fig. 5a, b) there also. Little is known, however, about the possible storage or turnover rates of K and Cs in the large masses of foliage and parenchymatous stems of bearing coconut.

Development from flower to mature copra nut occurs over a period of about one year. The nine month requirement for $^{137}Cs$ reduction, indicated above, concurs with the probable time for development of a "modal drinker" plus allowance for penetration and uptake of K applied to the soil surface. Thus, this requirement is not greatly affected by the quantity of K applied, within the range examined here—670 to 6300 kg K $ha^{-1}$ (Table 2).

In view of the above, the much longer time for near-maximum decrease of $^{137}Cs$ in Exps. I, II and III likely is due to a slow net accumulation of K from the ~quarterly applications. In Exp. I (Fig. 2), all fertilizer was added as plastic-encapsulated pellets, which delayed full solubility. Further, the first two applications were made during the dry winter period. In Exps. II and III (Figs. 3 and 4) only two-fifths of the applied K was plastic-encapsulated. More consequentially, however, NPK fertilizers were broadcast repeatedly over an 8.5-m radius around individual palms, favoring development of absorbing root masses by intruding lateral roots from surrounding palms. The resulting redistribution of successive applications over a much larger area would have reduced their effectiveness on the target palms. Such "poaching" by surrounding trees is a known problem in orchard fertilization research (Haines et al. 1954).

*Duration of K Response*

Once attained, the maximum reduction in $^{137}Cs$ (i.e., maximum response to K) persists for periods up to at least 30 to 45 months (Fig. 5, Table 4). In Exp. I (Fig. 2) the small but continuing increase in $^{137}Cs$, beginning 36 months after the last fertilizer application, probably signals an end to the suppressive effect of K, although that of P may then emerge. The first upturn in $^{137}Cs$ occurred about nine months after the exceptionally high cumulative rainfall of August to October 1986 (1090 mm on Bikini Island), which would have accelerated normal soil leaching.

### $^{137}Cs$ *in Grass and Moonvine*

Reduction of $^{137}Cs$ in grass following K application (Fig. 6) agrees with an earlier report from Rongelap Atoll by Walker, et al. (1961) but is larger and of longer duration. They had applied KCl at the rate of 130 kg K $ha^{-1}$ to a .005 ha plot of a different grass, *Lepturus repens* (Frost. f.), beneath coconut. Seven months later, $^{137}Cs$ in grass had decreased from 1.1 to 0.28 Bq $g^{-1}$ (29.5 to 7.5 pCi $g^{-1}$), (dry weight!), as compared with a control, whereas K had increased from 0.39 to 0.64%. These differences disappeared in the next six months, presumably because the relatively small addition was dissipated through uptake by roots of surrounding palms and, perhaps, by leaching.

In the present study, the decrease of $^{137}Cs$ in the controls between nine and thirty months somewhat obscures the similarity of response in coconut and grass. A likely cause for this large decrease is competition from redeveloping coconut roots in the disturbed soil surface. This is also suggested by recovery of drinking-nut $^{137}Cs$ concentration after nine months (Fig. 5a.).

### *Mechanism of Cs Suppression by K*

The mechanism(s) by which soil-applied K suppresses $^{137}Cs$ in the fruit of coconut is unknown. Paired plot comparison of $^{137}Cs$ surface-gamma emission across boundaries between control and K-treated plots gives no evidence that K has displaced $^{137}Cs$ from the surface soil. A more plausible and apparently widely accepted explanation is competition between the two ions for root uptake (Shaw and Bell 1989). Conceptual difficulties arise, however, when the disparity between concentrations of the two ions in Bikini soils and the modest increases in K brought about by even heavy applications are considered. The range of *exchangeable* K in Bikini soils is from ~$2.6 \times 10^{-4}$ to $10^{-3}$ mols $kg^{-1}$, whereas *total* $^{137}Cs$ ranges from about $10^{-12}$ to $10^{-11}$ mols $kg^{-1}$. Only about 3% of this total appears to be exchangeable

(Koranda et al. 1978; Robison et al. 1988). Application of 1000 kg K $ha^{-1}$, distributed to a depth of 10 cm, amounts to about 2.6 x $10^{-2}$ mols $kg^{-1}$. Such an addition overwhelms the existing levels of exchangeable K, but increases the already wide disparity between K and Cs by only one or two orders of magnitude. The suppressive effects of this K increase on $^{137}Cs$ in plants, however, are profound. Moreover, the ion-competition hypothesis, as formulated, cannot be readily reconciled with certain field observations. In Exp. IV, the mean decreases in drinking-nut $^{137}Cs$ at 33 months for palm rows bordering $K_1$ rows (hence fertilized on only one side) were about 90% as great as for palms fertilized on both sides, rather than 50%. Hypotheses that would account for such an effect are yet to be tested.

Nevertheless, further observations in these same rows and others demonstrate that increasing the area of K-treated soil around palms with unconfined root systems further lowers $^{137}Cs$ concentrations in nuts. The results of Exp VIII (Table 4) concur with such observations, although the effects of the enlarged treatment area in this case cannot be separated from those due to increasing K concentration within the original plot boundaries.

*Phosphorus Effects*

The unanticipated ~50% reduction in $^{137}Cs$ (Figs. 5a, b) following the NP treatment has been duplicated in a less extensive study nearby. The reductions have been maintained for more than 63 months in both studies. The latter observations suggest that P rather than N is the effective element inasmuch as unabsorbed N is rapidly lost from such soils whereas all P is retained.

As with K, there is no certain explanation of how P suppresses uptake of Cs. Numerous related studies with other species, however, provide ingredients for a plausible hypothesis: 1) Coconut roots are known to be colonized by vesicular-arbuscular (VA) mycorrhizae (Thomas and Ghai 1987; Thomas 1988); examinations of roots from Bikini confirm abundance of internal hyphae. 2) As noted by Sylvia and Neal (1990), accounts of P suppressing root colonization by VA fungi are numerous, although there are also accounts of no effect and of selection for P-tolerant fungi on high P soils. Sylvia and Neal's own studies with onion demonstrated suppressive effects of added P when internal supplies of N were sufficiently high. 3) Colonization of roots by VA mycorrhizae has increased uptake of Cs as well as Co (Rogers and Williams, 1986) Whether similar processes are operative in large palms growing in atoll soils is yet to be examined.

## APPLICATION OF RESULTS

We have not determined the minimum quantities of K required for maximum suppression of $^{137}Cs$ effectiveness in bearing groves with a ground cover of grass and herbs. Moreover, our experimental areas are not systematically harvested, which would entail an appreciable annual loss of K. In Exp. VII (Fig. 9), however, addition of 670 kg K $ha^{-1}$ over the entire root system rapidly reduced $^{137}Cs$ in drinking-nut meat from a mean of ~4.8 to ~1.1 Bq $g^{-1}$ (~130 to ~30 pCi $g^{-1}$) Application of 1260 kg K $ha^{-1}$ to palms initially higher in $^{137}Cs$, 6.3 to 7.4 Bq $g^{-1}$ (170 to 200 pCi $g^{-1}$), lowered these levels to ~0.93 Bq $g^{-1}$ (~25 pCi $g^{-1}$) or less (Fig. 5), and somewhat further when treatment width was expanded from 8.53 to 17.1 m on either side of the row. Neither doubling the rate of K nor combination with N and P had any certain effect in further reducing $^{137}Cs$ over a 33 month period (Fig. 5).

The lag time between application of K and the major—not necessarily maximum—reduction of $^{137}Cs$ in drinking-nut meat and fluid is eight to nine months, or somewhat longer if a rainless period follows application. This time seems independent of K rate, above some level of adequacy. The minimum level of $^{137}Cs$ attained through single applications of K is influenced by the pre-treatment level. Probably it is affected by amount of applied K at or near the lower limits of adequacy, but apparently not above 1200 kg $ha^{-1}$. Distribution of the applied K over the whole area of the root system seems to achieve maximum reduction, but reduction is not proportional to the percentage of root area treated.

Once achieved, the reduction can persist for at least 36 to 63 months after application, although perhaps diminishing slowly (Fig. 2, Table 4). Probably the effects of lower rates will persist for shorter times. The main determinants of persistence, however, probably are the total amount of soil organic matter, which retains K, and the amount of excess rainfall leaching through the soil. For this reason, scheduling applications of 600 to 1000 kg K $ha^{-1}$ at three-year intervals is likely to prove more effective and cost efficient than larger applications at longer intervals.

Coconut palms have a high requirement for K, both through the juvenile development stage and to meet the needs of nut production and harvest removals. Applications suggested for tall varieties are in the range of one to three kg $palm^{-1}$ $year^{-1}$, or 135 to 410 kg $ha^{-1}$ $yr^{-1}$ at 8.5- x 8.5-m spacing. At such rates, the cumulative three-year addition for production purposes would approach or overlap our suggested application of 600–1000 kg $ha^{-1}$ every three years to suppress $^{137}Cs$ uptake, thus achieving both purposes.

Present knowledge of the suppressive effects of K on $^{137}Cs$, especially the interactions with rainfall, is incomplete. It is therefore desirable that application of K to reduce $^{137}Cs$ in human or domestic animal diets be accompanied by periodic monitoring to assure that the expected results are attained.

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at 48 months to seven previous +K plots and one NP plot. Dotted lines indicate subsequent courses. Vertical lines indicate range around mean.

Figure 7a,b Experiment V. Response of $^{137}Cs$ concentrations in drinking-nut meat (a) and fluid (b) after application of 6270 kg K $ha^{-1}$ to single palm plots. The unconnected circles and squares indicate one SEM (n = 3 to 5).

Figure 8a,b Experiment VI. Effect of 3740 kg K $ha^{-1}$ applied in August 1987 on palms with low concentrations (~ 0.75 Bq $g^{-1}$) in drinking-nut meat (a) and fluid (b). The unconnected circles and squares indicate one SEM for six to nine palms per plot.

Figure 9a,b Experiment VII. Effect of 670 kg K $ha^{-1}$ applied August 1989 on $^{137}Cs$ concentration in drinking-nut meat (a) and fluid (b). The unconnected circles and squares indicate one SEM for 12 to 16 palms per plot.

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Table 1. Composition of coral soil from Bikini and Eneu Islands.

| Island location and depth (cm) | pH[a] | $^{137}Cs$ (Bq/g) | $^{90}Sr$[b] (Bq/g) | Total[c] Sr (%) | Ca (%) | Mg (%) | P[d] (%) | N (%) | Organic matter[e] (%) | Extractable K[f] (ppm) | Particles sized <0.5 mm (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bikini No. 1 | | | | | | | | | | | |
| 0–5 | 7.7 | 10.4 | 2.4 | 0.38 | 30.4 | 0.95 | 1.35 | 0.64 | 14.4 | 79 | 11.5 |
| 5–10 | 7.8 | 3.2 | 2.7 | 0.39 | 30.8 | 0.89 | 1.28 | 0.62 | 13.2 | 26 | |
| 10–15 | 7.9 | 1.3 | 2.3 | 0.39 | 30.9 | 0.89 | 1.29 | 0.63 | 12.3 | 20 | 9.5 |
| 15–25 | 7.9 | 0.82 | 1.4 | 0.40 | 31.9 | 0.86 | 1.17 | 0.50 | 10.6 | 23 | 11.7 |
| 25–40 | 8.3 | 0.13 | 0.89 | 0.39 | 34.3 | 1.28 | 0.67 | 0.19 | 4.5 | 4 | 6.3 |
| 40–60 | 8.4 | 0.041 | — | 0.31 | 34.5 | 2.05 | 0.16 | 0.11 | 1.6 | 3 | 0.6 |
| Bikini No. 2 | | | | | | | | | | | |
| 0–5 | 7.8 | 4.4 | 2.4 | 0.40 | 31.0 | 1.02 | 0.82 | 0.49 | 10.7 | 50 | 5.7 |
| 5–10 | 8.0 | 2.0 | 2.7 | 0.40 | 32.4 | 1.09 | 0.71 | 0.46 | 8.5 | 24 | 3.7 |
| 10–15 | 7.9 | 0.78 | 2.3 | 0.38 | 33.1 | 1.18 | 0.56 | 0.35 | 7.4 | 24 | 3.3 |
| 15–40 | 8.2 | 0.16 | 1.2 | 0.38 | 34.7 | 1.79 | 0.32 | 0.11 | 1.6 | 6 | 1.1 |
| Eneu No. 1 | | | | | | | | | | | |
| 0–5 | 7.7 | 0.3 | 0.085 | 0.32 | 32.0 | 1.74 | 0.085 | 0.30 | 5.1 | 41 | 2.3 |
| 5–10 | 8.0 | 0.25 | 0.096 | 0.34 | 32.6 | 1.76 | 0.055 | 0.35 | 5.6 | 20 | 1.6 |
| 10–15 | 8.0 | 0.093 | 0.10 | 0.31 | 34.4 | 2.08 | 0.037 | 0.17 | 2.6 | 9 | 0.8 |
| 15–25 | 8.4 | 0.0037 | 0.093 | 0.28 | 34.0 | 2.40 | 0.016 | 0.06 | 0.9 | 1 | 0.3 |
| 25–40 | 8.7 | 0.0037 | 0.089 | 0.28 | 34.4 | 2.48 | 0.014 | 0.05 | 0.8 | 1 | 0.2 |
| 40–60 | 8.9 | 0.0074 | — | 0.30 | 33.3 | 2.37 | 0.015 | 0.03 | 0.6 | <1 | 0.1 |

[a] pH in water.

[b] The strontium-90 activities are the mean of 55–63 sites on Bikini and 37–40 on Eneu. The activity at locations 1 and 2 on Bikini and Eneu Islands was not determined.

[c] Stable cesium was below detection limit (1.3 ppm).

[d] High phosphorus values indicate ancient guano deposition.

[e] Organic matter by wet oxidation.

[f] Extractable in N $NH_4$ acetate.

Table 2. Synopsis of design, treatments and characteristics of experiments with bearing coconut palms.

| Exp. No. | Begun yr | Duration months | Design, treatment, gross plot area | Carrier | Fertilizer Total Applied N kg/ha | P kg/ha | K kg/ha | Min treated radius m |
|---|---|---|---|---|---|---|---|---|
| Eneu Island | | | | | | | | |
| I | 1980 | 112 | One 0.065 ha 4-palm plot. Ten applications NPK/3 yr. | 13.7-6.4-10* | 2870 | 615 | 1830 | 8.5 |
| II | 1983 | 94 | Four 8.53 m radius single-palm plots (0.023 ha); roots unconfined. Thirteen applications NPK/3 1/2 yr. | 13.7-6.4-10*<br>16-16-16 | 2640 | 975 | 2190 | 8.5 |
| Bikini Island | | | | | | | | |
| III | 1983 | 94 | Five 8.53 m radius single-palm plots (0.023 ha); roots unconfined. Thirteen applications NPK/3 1/2 yr. | 13.7-6.4-10*<br>16-16-16 | 3300 | 1080 | 2400 | 8.5 |
| IV | 1985 | 33 | K x (NP) factorial, 3 x 2 x 2 repl. Ten-palm row plots, 0.16 ha with 8.5 m separations. Four applications/9 months. | KCl ($K_1$)<br>KCl ($K_2$)<br>26-26-0 ($NP_1$) | 0<br>0<br>530 | 0<br>0<br>230 | 1260<br>2520<br>0 | 8.5 |
| V | 1986 | 45 | $K_0$ vs $K_1$, 2 x 5 repl., complete randomization. Single-palm plots, 73 $m^2$, with subsoiled boundaries. Single application. | KCl | 0 | 0 | 6270 | n.a. |
| VI | 1987 | 33 | $K_0$ vs $K_1$, unreplicated. 10-palm plots with treated borders, 0.16 ha. Single application. | KCl | 0 | 0 | 3740 | 17.1** |
| VII | 1988 | 27 | $K_0$ vs $K_1$, unreplicated. 20-palm plots with treated borders, 0.408 ha. Single application. | KCl | 0 | 0 | 670 | 17.1 |
| VIII | 1989 | 12 | $K_0$ vs $K_1$. Exp IV area reblocked and boundaries subsoiled. Two blocks, 0.63 and 1.9 ha refertilized over all. Two blocks, 0.63 ea., are controls and contain Exp. IV controls. Single application. | KCl | 0 | 0 | 1120 | n.a. |

* "Osmocote, tropical" — plastic encapsulated pellets; ** 8.53 m at plot ends.

**Table 3. Experiment IV. Results of Duncan's multiple range tests (p = 0.10) for $^{137}Cs$ in drinking nut meat and fluid.**

| | Sample Date — Months after first application | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0 | 9 | 12 | 15 | 18 | 21 | 26 | 30 | 33 |
| | | | | | Meat | | | | |
| Main Effects | | | | | | | | | |
| $K_0$ | A[a] | A | A | A | A | A | A | A | A |
| $K_1$ | A | B | B | B | B | B | B | B | B |
| $K_2$ | A | B | C | C | B | B | B | B | C |
| $NP_0$ | A | A | A | A | A | A | A | A | A |
| $NP_1$ | A | B | B | B | B | B | B | B | B |
| Simple Effects | | | | | | | | | |
| $K_0NP_0$ | A | A | A | A | A | A | A | A | A |
| $K_0NP_1$ | AB | B | B | B | B | B | B | B | B |
| $K_1NP_0$ | B | C | DC | C | C | C | C | C | C |
| $K_1NP_1$ | AB | C | C | C | C | C | C | C | CD |
| $K_2NP_0$ | AB | DC | D | D | C | C | C | C | DE |
| $K_2NP_1$ | AB | D | D | D | C | C | C | C | E |
| | | | | | Fluid | | | | |
| Main Effects | | | | | | | | | |
| $K_0$ | — | A | A | A | A | A | A | A | A |
| $K_1$ | — | B | B | B | B | B | B | B | B |
| $K_2$ | — | B | C | C | B | B | B | B | B |
| $NP_0$ | — | A | A | A | A | A | A | A | A |
| $NP_1$ | — | A | A | B | B | B | B | B | B |
| Simple Effects | | | | | | | | | |
| $K_0NP_0$ | — | A | A | A | A | A | A | A | A |
| $K_0NP_0$ | — | BC | B | B | B | B | B | B | B |
| $K_1NP_1$ | — | B | D | CD | C | C | C | C | CD |
| $K_2NP_0$ | — | C | D | DE | C | C | C | C | D |
| $K_2NP_1$ | — | C | D | E | C | C | C | C | E |

[a] Within sample date (column), values represented by the same letter do not differ significantly. See Figure 5a,b.

**Table 4. Experiment VIII. Mean $^{137}Cs$ concentration in drinking nut meat from the same individual palms, before and 12 months after application of K to subdivisions of the former Experiment IV area.**

| K, kg/ha | | | $^{137}Cs$, Bq/g, wet wt. | | P |
|---|---|---|---|---|---|
| Treatment[a] | | | Drinking nut meat | | Significance |
| 0–9 mo | 51 mo | n | 51 mo | 63 mo | of difference |
| "Controls" | | | | | |
| 0 | 0 | 14 | 4.9 | 4.7 | n.s |
| 0 + NP | 0 | 4 | 2.7 | 2.6 | n.s. |
| 2520 | 0 | 8 | 0.74 | 1.2 | <.001 |
| "Re-treated"[b] | | | | | |
| 1260 | 1120 | 11 | 0.85 | 0.41 | <.0005 |
| 1260 + NP | 1120 | 16 | 0.78 | 0.41 | <.0005 |
| 2520 | 1120 | 8 | 1.1 | 0.48 | <.0005 |
| 2520 + NP | 1120 | 15 | 0.59 | 0.33 | <.0005 |

[a] The 0, 1260 and 2520 kg/ha treatments correspond to individual $K_0$, $K_1$ and $K_2$ plots, respectively, in Table 3 and Figure 5.

[b] "Re-treatment" extended beyond the Exp. IV plot boundaries so that all or most of the roots were in K-treated soil.

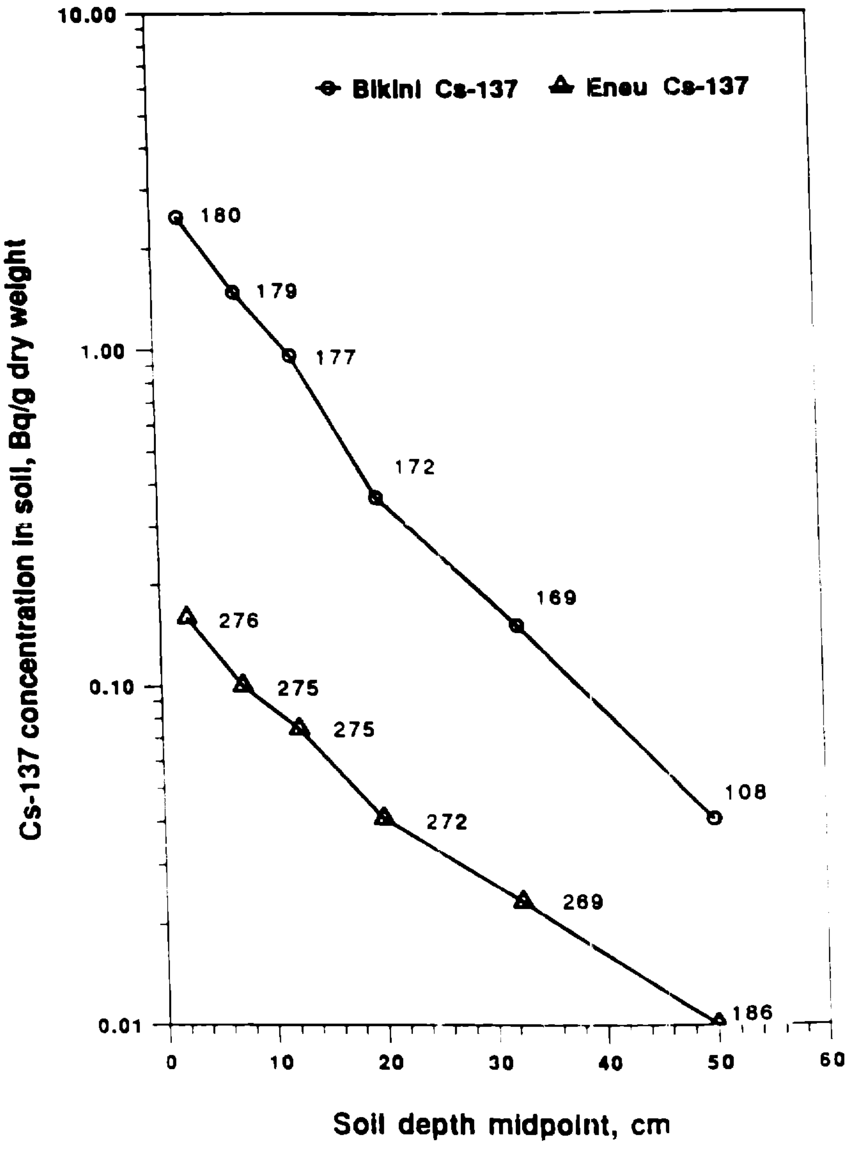



Figure 1 Mean distribution of $^{137}Cs$ with soil depth on Bikini and Eneu Islands.

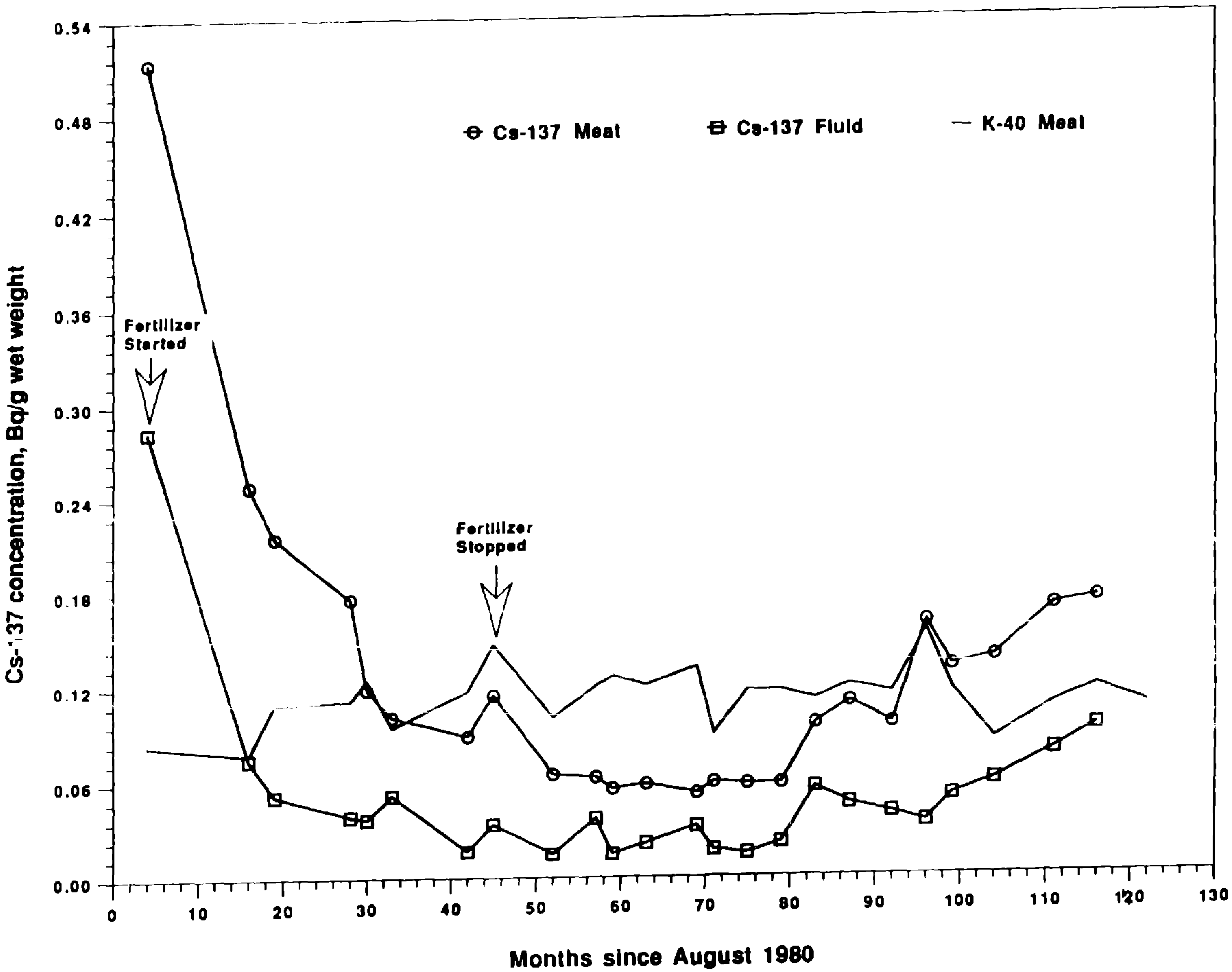



Figure 2 Experiment I. Effect of 10 NPK additions on mean $^{137}Cs$ concentrations in drinking-nut meat and fluid from three to four palms on a 25.5 x 25.5 m plot. Arrows mark the beginning and end of fertilization period. Eneu Island.

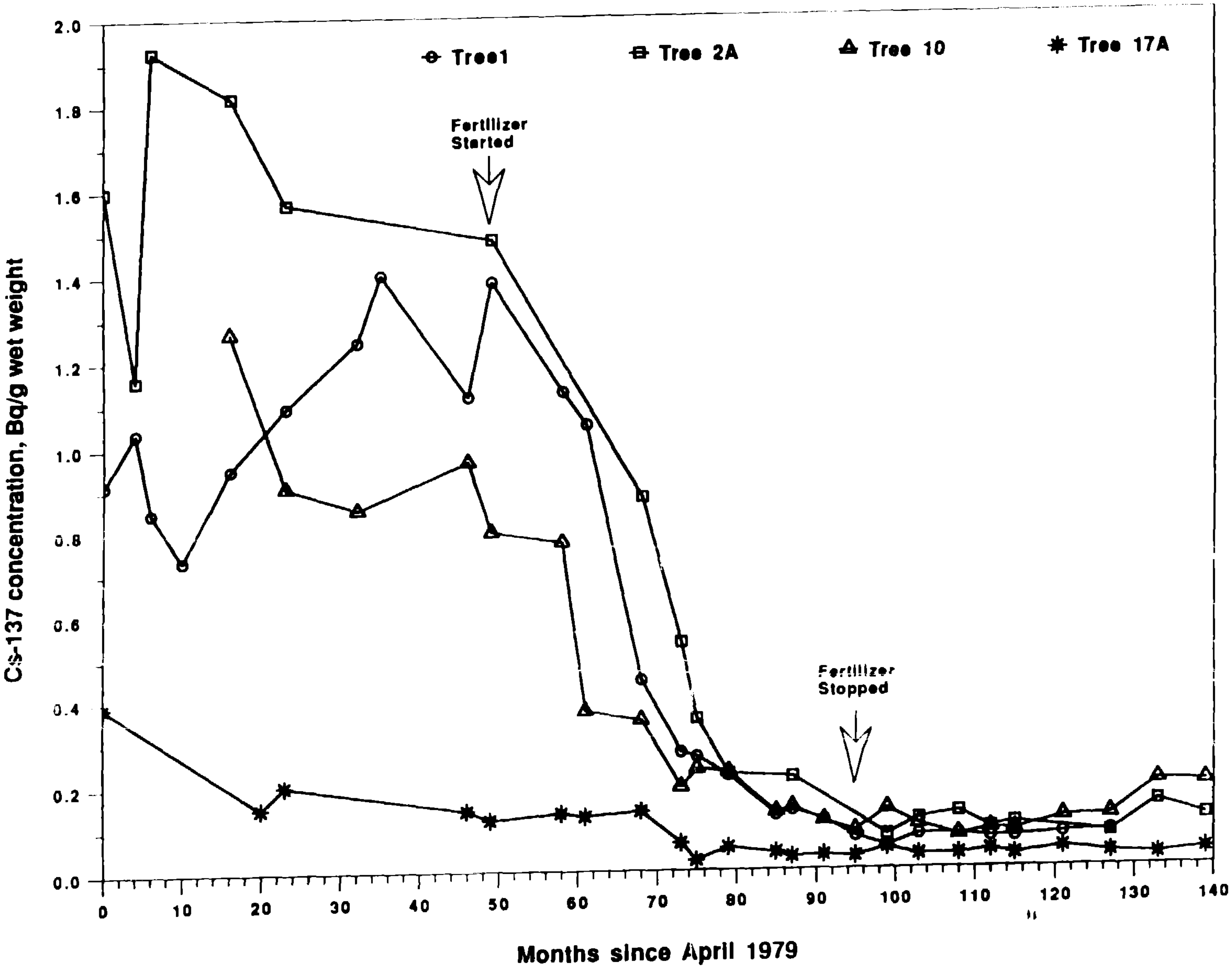



Figure 3a,b Experiment II. Effect of 13 applications of NPK on $^{137}Cs$ concentrations of drinking-nut meat (a) and fluid (b) from four palms representing the range of initial concentrations. Arrows mark the beginning and end of fertilizer application to 8.5-m radius around each palm. Eneu Island.

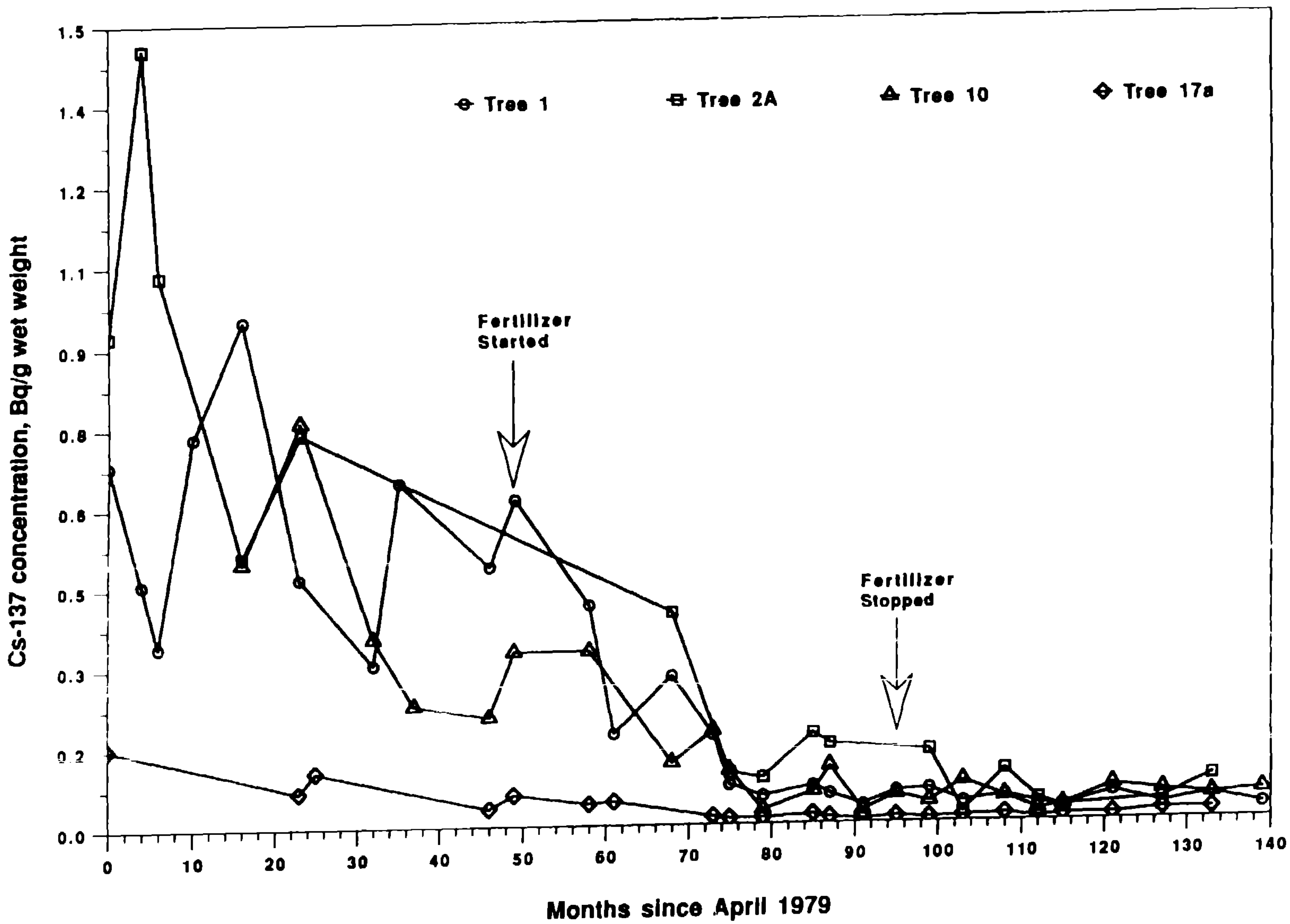



Figure 3a,b Experiment II. Effect of 13 applications of NPK on $^{137}Cs$ concentrations of drinking-nut meat (a) and fluid (b) from four palms representing the range of initial concentrations. Arrows mark the beginning and end of fertilizer application to 8.5-m radius around each palm. Eneu Island.

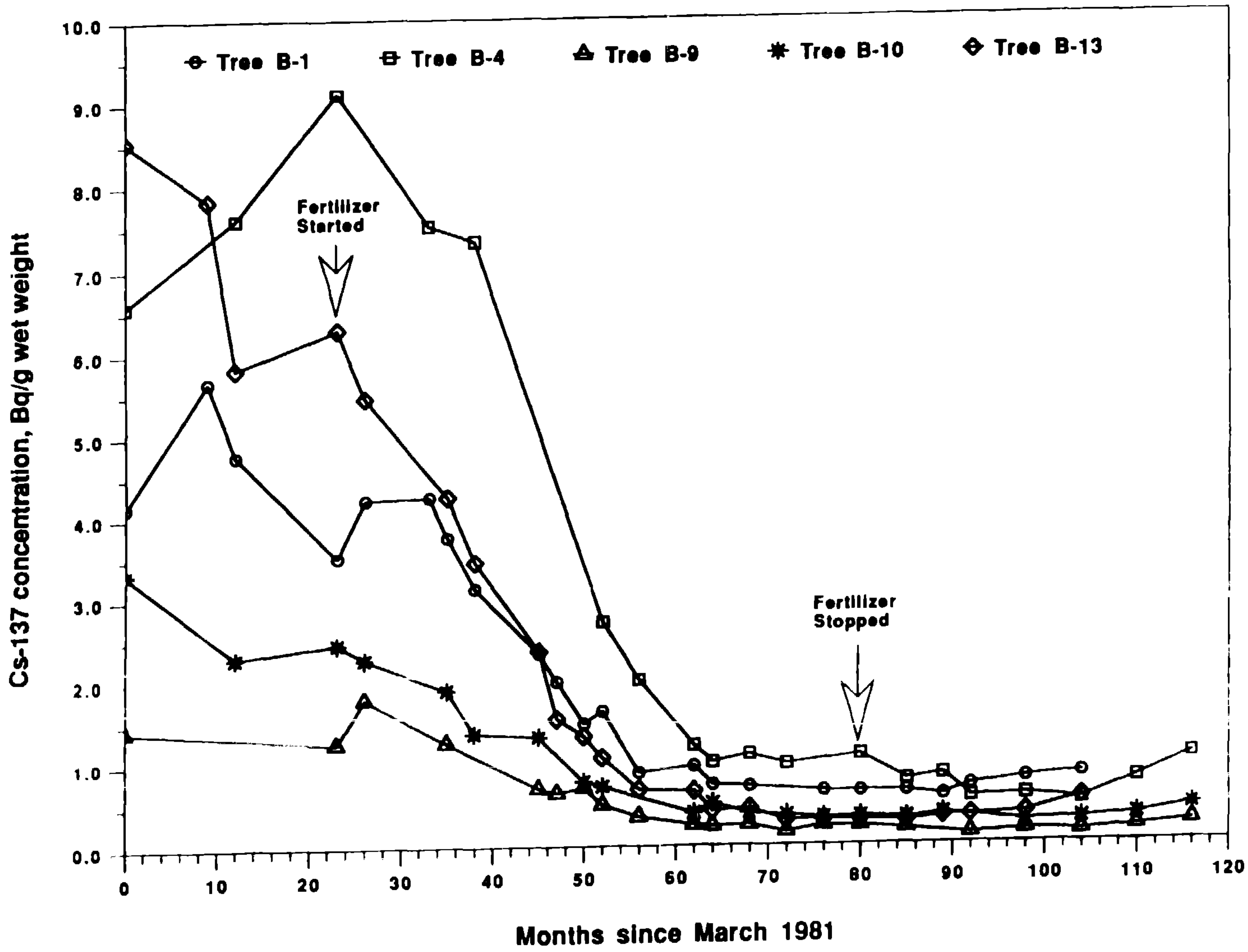



Figure 4a,b Experiment III. As for Figure 3a,b but on Bikini Island. Note difference in ordinal scales of the two islands.

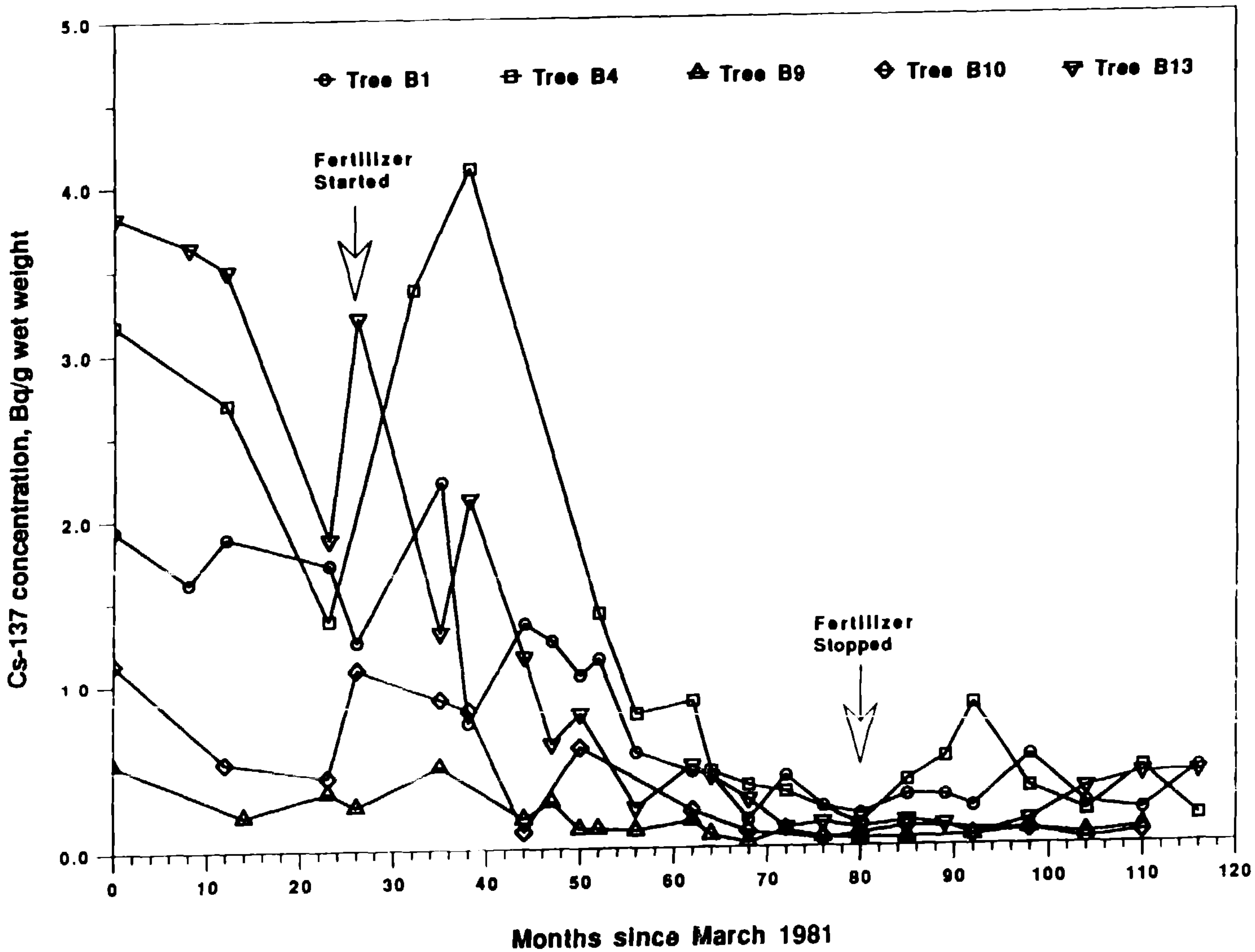



Figure 4a,b Experiment III. As for Figure 3a,b but on Bikini Island. Note difference in ordinal scales of the two islands.

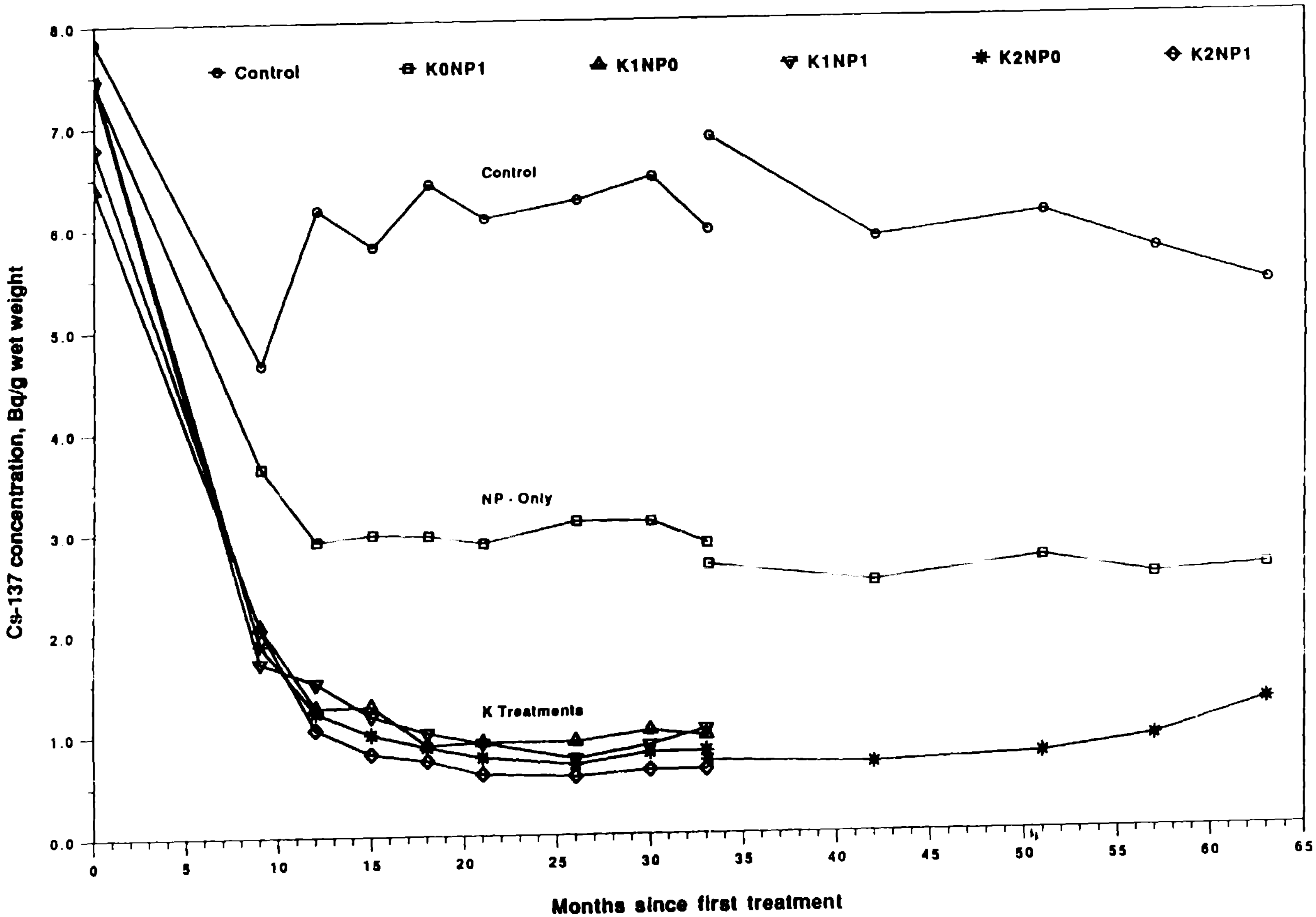



Figure 5a Experiment IV. Response of drinking-nut $^{137}Cs$ concentrations to 0, 1260 and 2520 kg $ha^{-1}$ K ($K_0$, $K_1$, K) and/or combined NP treatment, applied as four equal additions over nine months. Values to 33 months are weighted plot means (See Table 3). Values for 33 to 63 months (solid symbols) are means (n = 6 to 10) from single plots unaffected by further treatment.

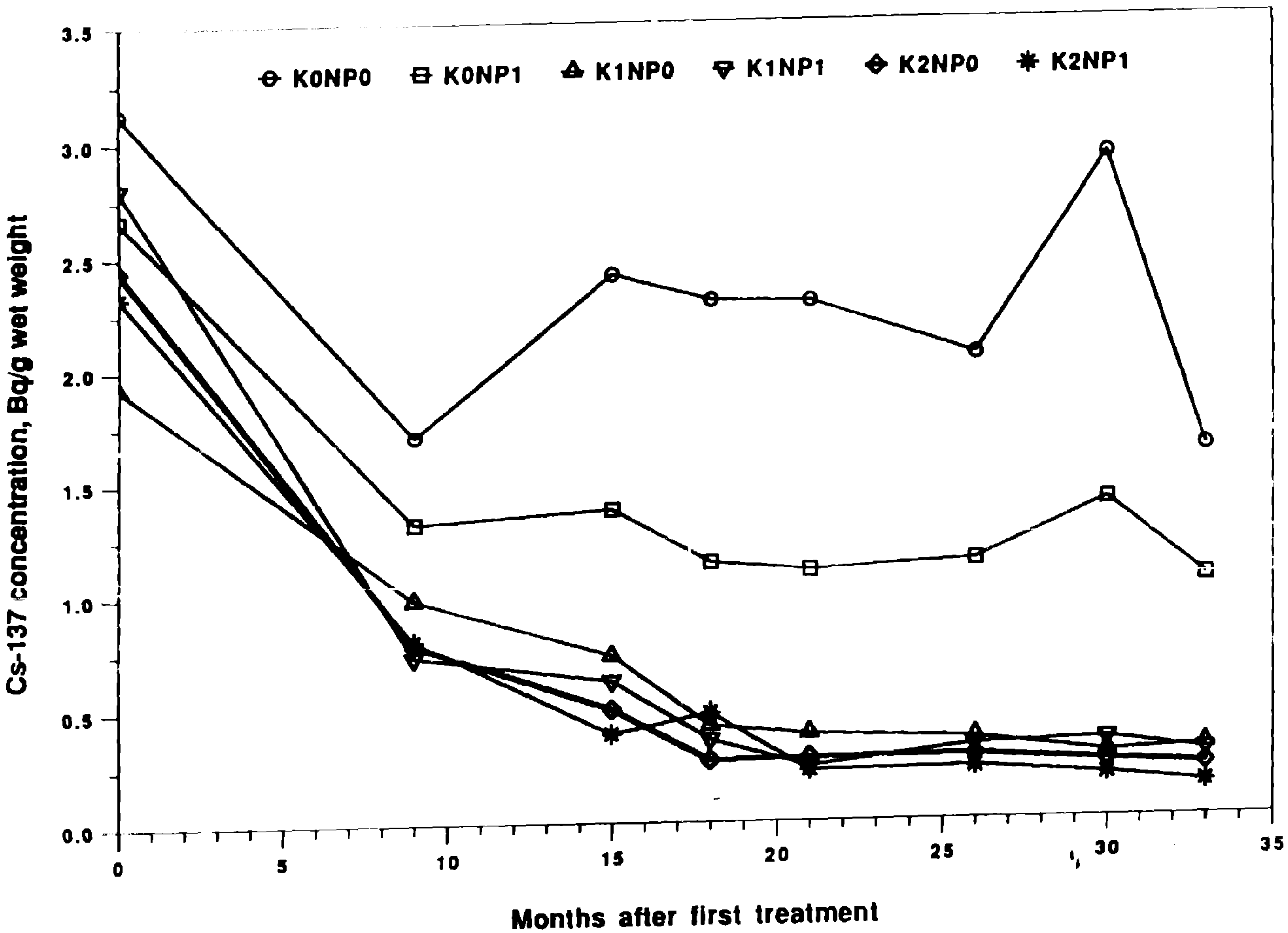



Figure 5b Experiment IVa. Response of drinking-nut fluid concentrations of $^{137}Cs$ in same experiment as 5a.

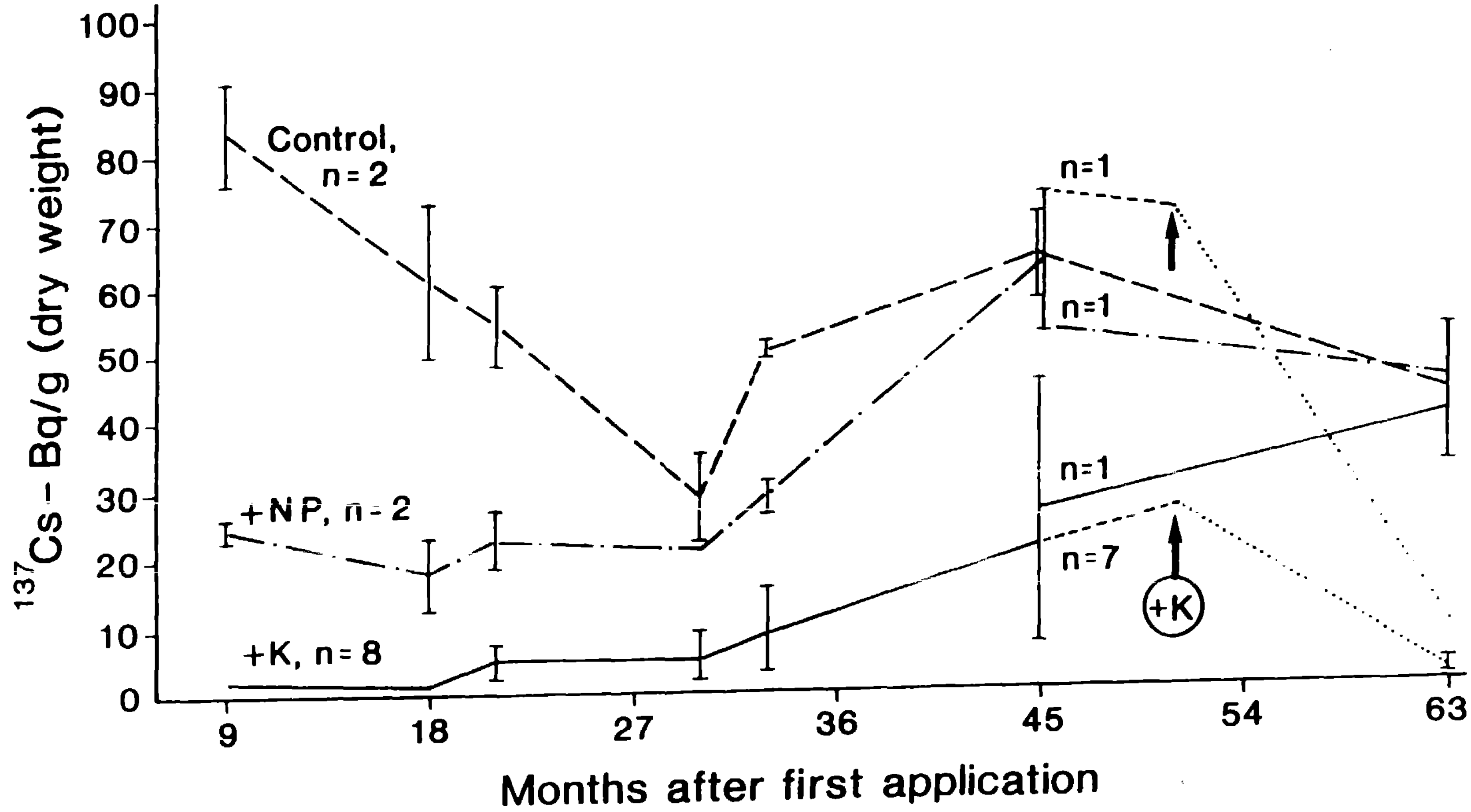



Figure 6 Experiment IV. Changes in $^{137}Cs$ concentration (dry weight basis) in an understory grass, *Eustachys petraea*, following 1) application of K (± NP) or NP alone at 0, 3 and 6 months, and 2) reapplication of K (arrows) at 48 months to seven previous +K plots and one NP plot. Dotted lines indicate subsequent courses. Vertical lines indicate range around mean.

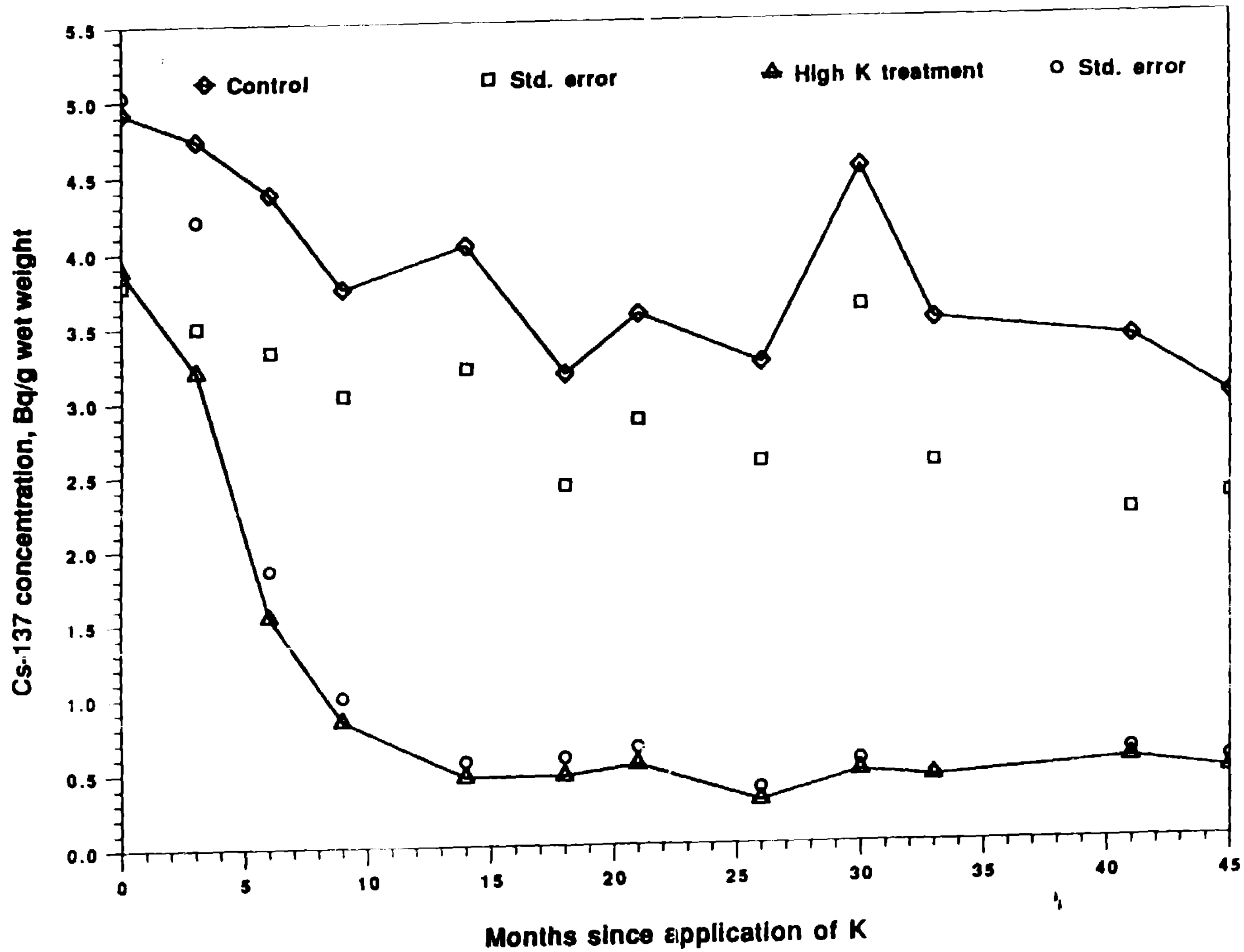
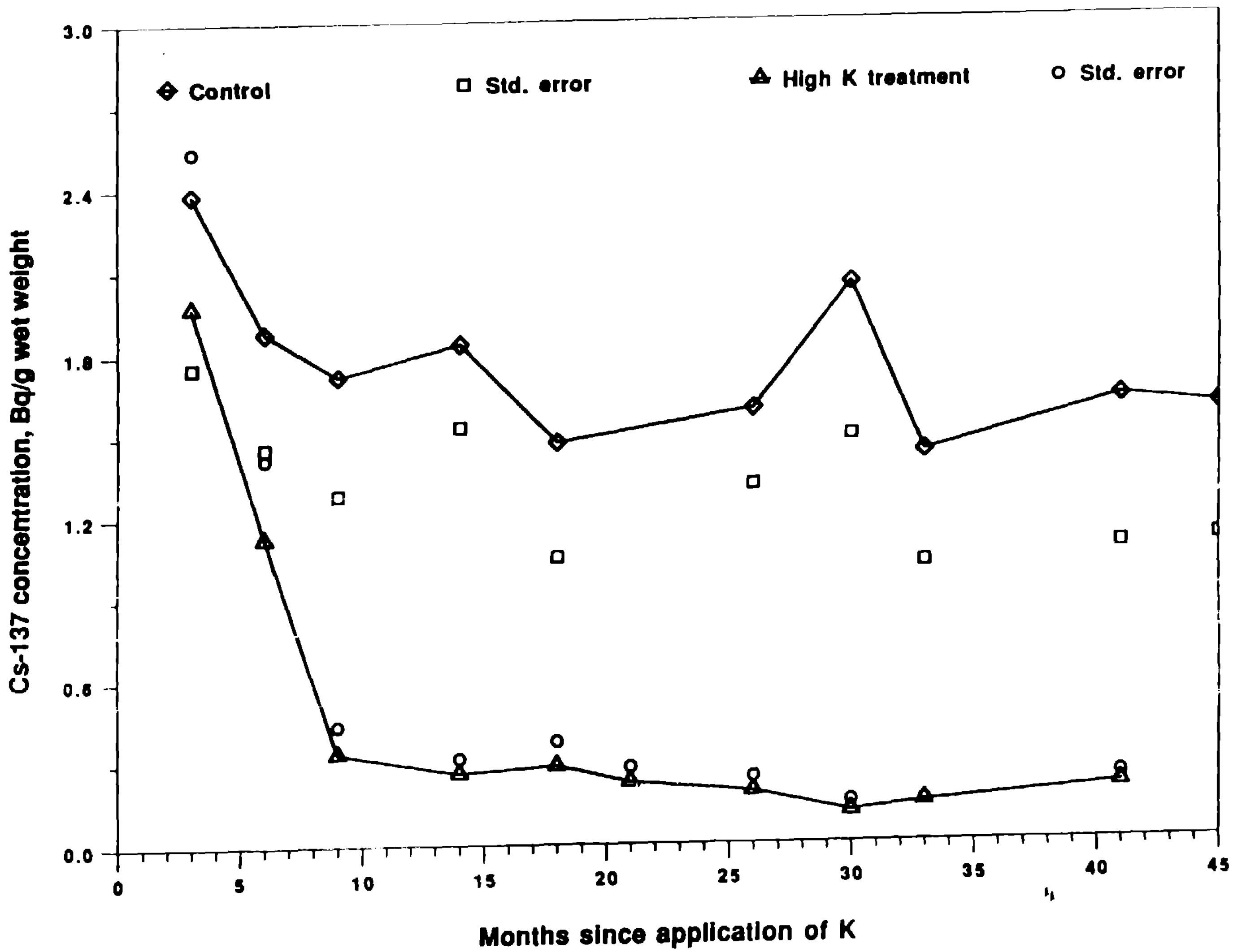



Figure 7a,b Experiment V. Response of $^{137}Cs$ concentrations in drinking-nut meat (a) and fluid (b) after application of 6270 kg K $ha^{-1}$ to single palm plots. The unconncected circles and squares indicate one SEM (n = 3 to 5).

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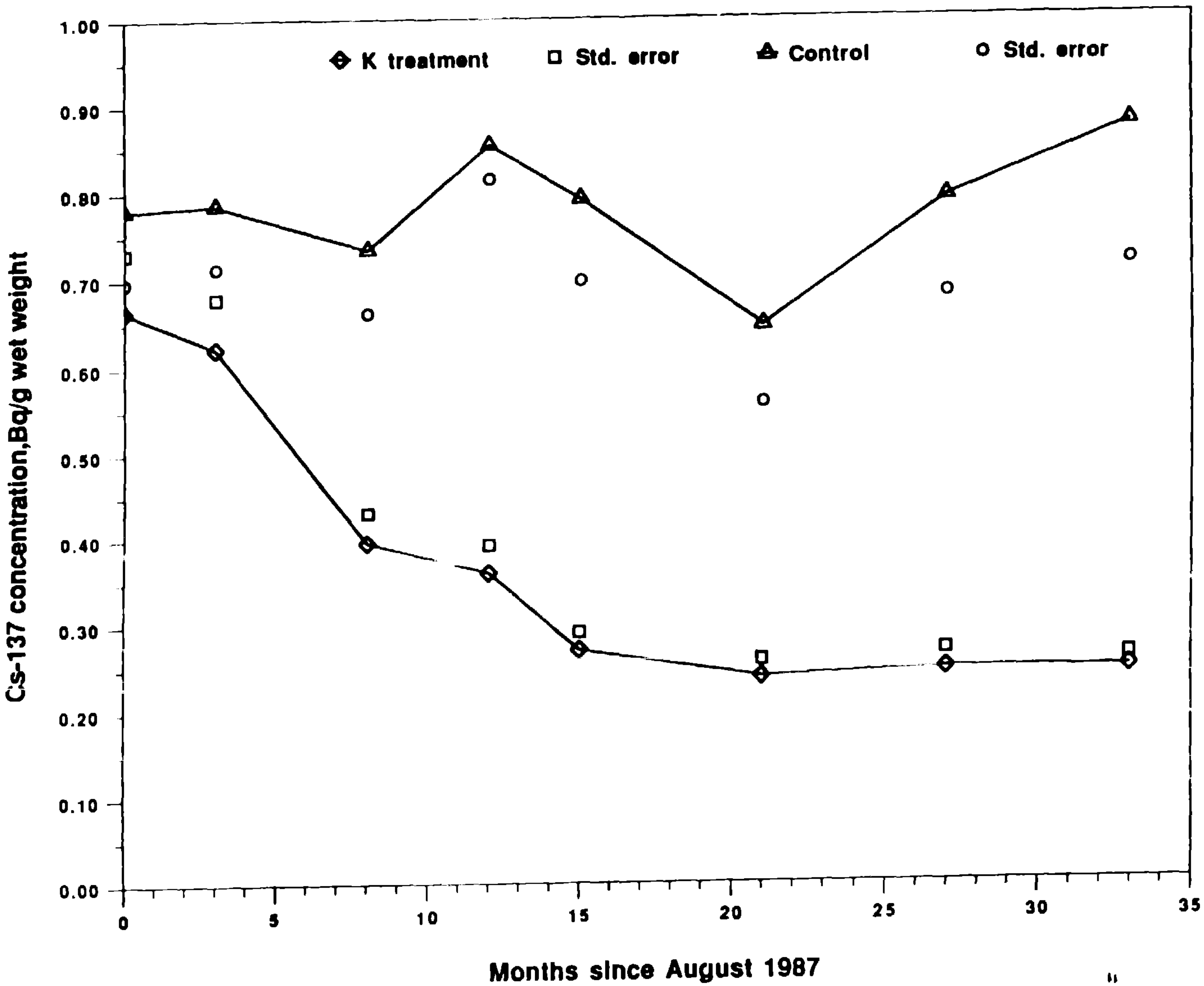
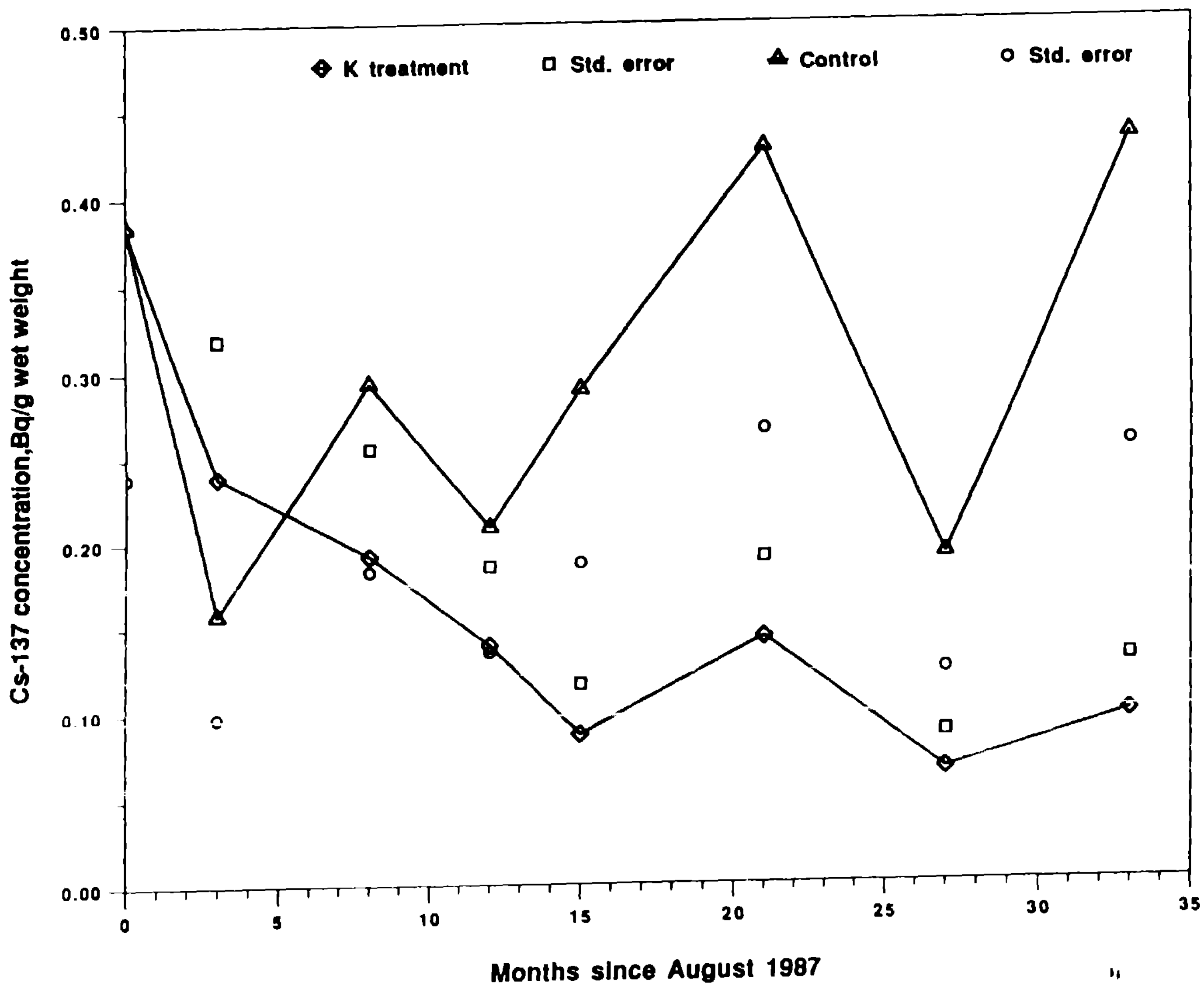



Figure 8a,b Experiment VI. Effect of 3740 kg K $ha^{-1}$ applied in August 1987 on palms with low concentrations (~ 0.75 Bq $g^{-1}$) in drinking-nut meat (a) and fluid (b). The unconnected circles and squares indicate one SEM for six to nine palms per plot.

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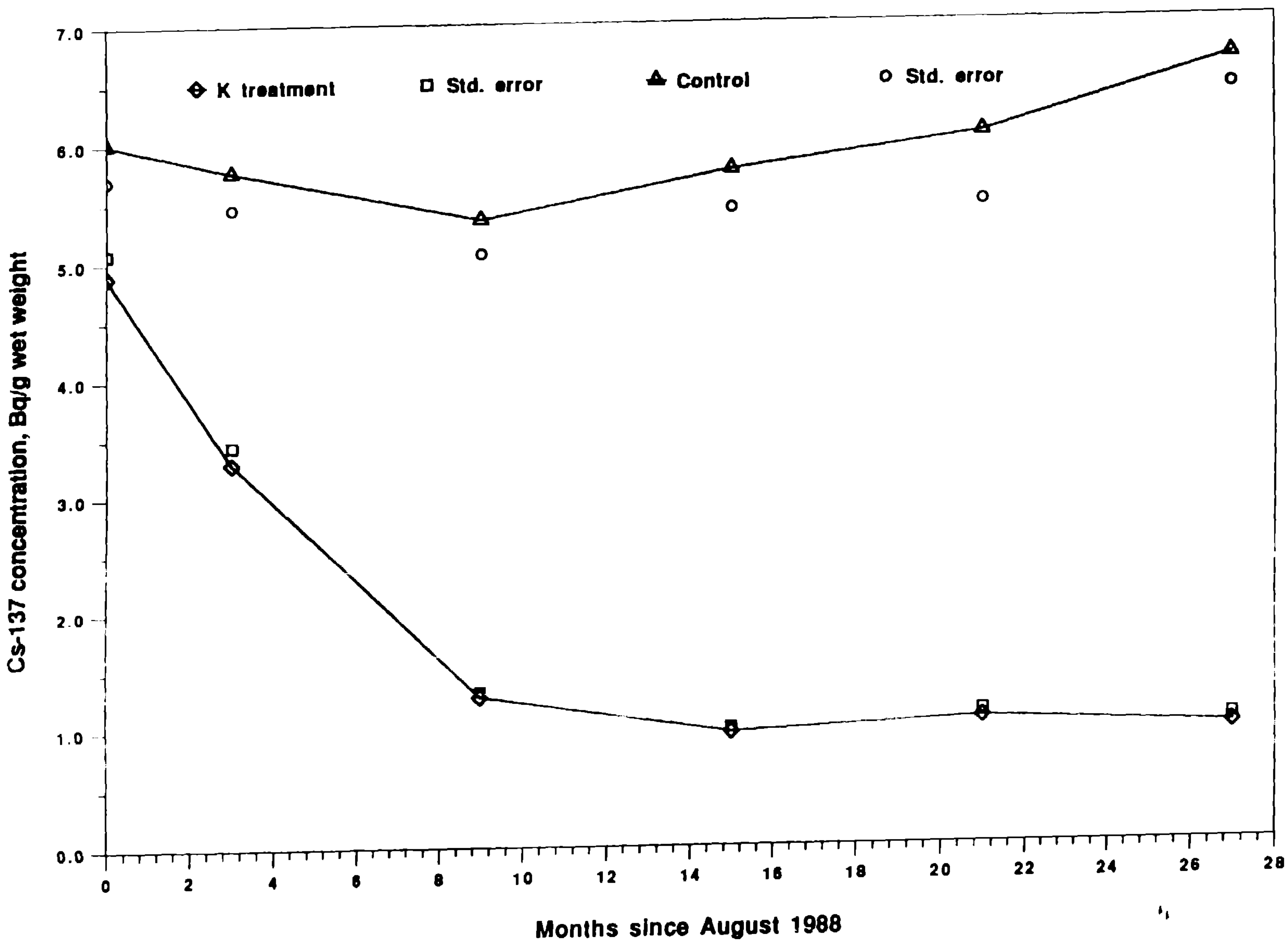


Figure 9a,b Experiment VII. Effect of 670 kg K $ha^{-1}$ applied August 1989 on $^{137}Cs$ concentration in drinking-nut meat (a) and fluid (b). The unconnected circles and squares indicate one SEM for 12 to 16 palms per plot.

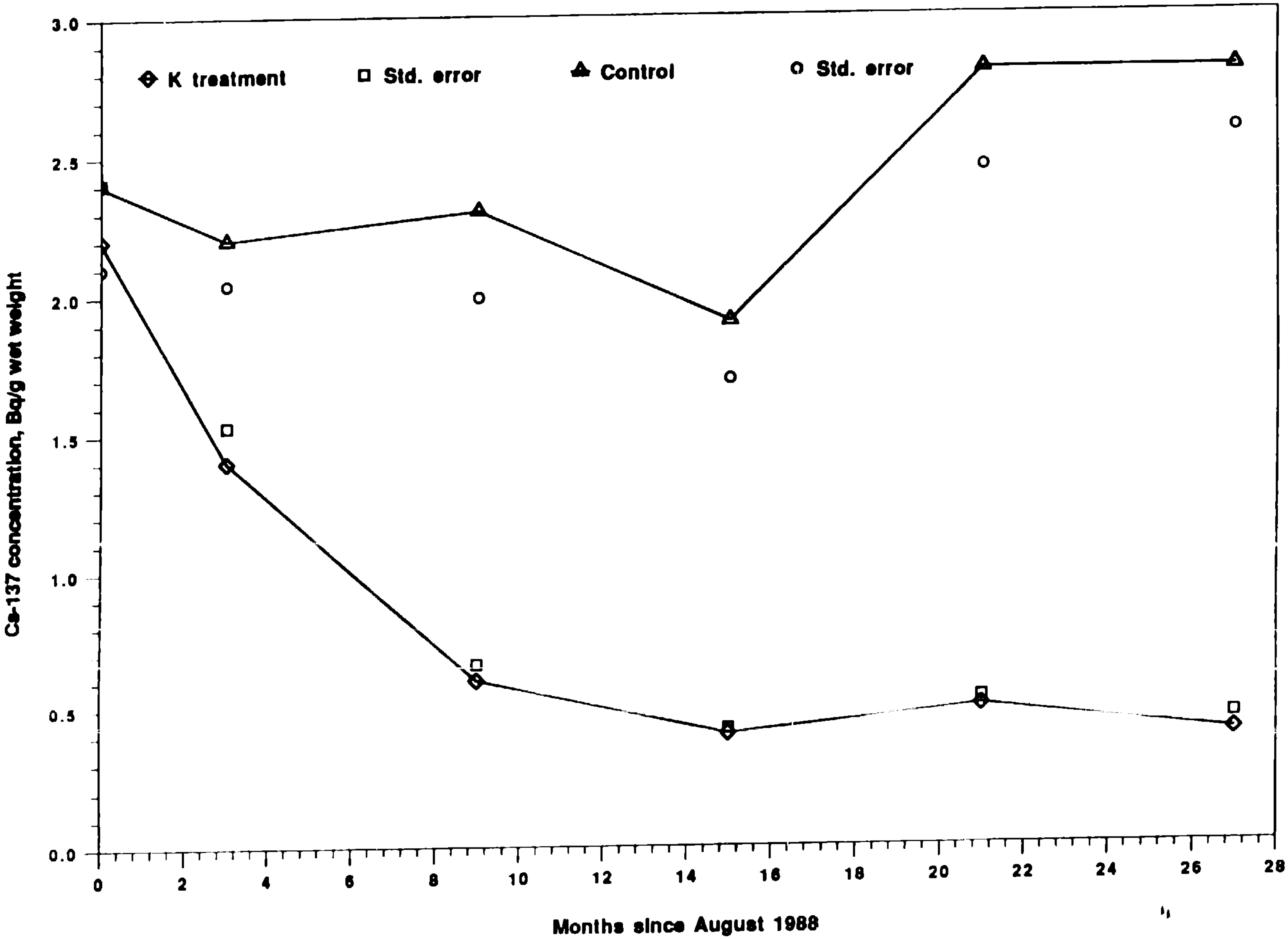


Figure 9a,b Experiment VII. Effect of 670 kg K $ha^{-1}$ applied August 1989 on $^{137}Cs$ concentration in drinking-nut meat (a) and fluid (b). The unconnected circles and squares indicate one SEM for 12 to 16 palms per plot.